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Soil-site relations for trembling aspen (Populus tremuloides Michx.) in Northwestern Ontario

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Soil-site Relations for Trembling Aspen (*Populus tremuloides* Michx.) in Northwestern Ontario

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ABSTRACT

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Keywords: site quality, site index, soil-site relations, trembling aspen (*Populus tremuloides*. Michx.), glaciofluvial, morainal, lacustrine.

Soil-site relations for trembling aspen in Northwestern Ontario were studied using 98 site plots representing a wide range of glacial landforms, soil conditions, and site quality. Site index was related to features of soil and topography using multivariate statistical analyses including principal component analysis, multiple regression analysis and cluster analysis. Site index (SI = height of dominant and codominant trembling aspen trees at 50 years breast-height age) was used as the dependent variable; 45 soil and topographic values were used as independent variables. Principal component analysis combined with correlation coefficients was used to select 10 variables from 22 variables that were closely associated with site index; these 10 variables are not closely correlated with each other. Preliminary regressions indicated that the soil-site relationships were much better expressed when plots were stratified into three landform types as opposed to a single regression combining all plots.

Final regression equations were computed describing soil-site relationships on soils developed from glaciofluvial, morainal, and lacustrinal landforms. The final regression equation for the glaciofluvial soils included depth to root restricting layer and drainage class as site-index predictor variables. The final regression equation for the morainal soils included silt plus clay content of the A horizon, coarse fragment content of the C horizon, and depth to root restricting layer. The final regression equation for the lacustrine soils included the clay content of the C horizon, and depth to mottles.

The 98 plots were clustered into six groups representing different soil conditions. The FEC soils S3, S4, S5 were the best sites; the SS8, SS7, S7, S8, SS5, SS4 were the worst sites for aspen. However, cluster results were not significant due to a wide range of site indices within each of the six defined groups. Large standard deviations and standard errors of the mean exist in most groups. Thus the use of these groups is not recommended for estimating aspen site index.

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INTRODUCTION

World forestry is entering a new era where population growth and industrial expansion has greatly multiplied demands for timber products. But the area of forest land available for producing timber has been reduced because of increasing needs for agricultural, urban and recreational use. Thus forest managers need to practice more intensive forest management aimed at producing increased quantities of high quality wood, from reduced areas of land at the lowest possible cost (Carmean, 1975; Thrower, 1986).

Determination of land productivity for several tree species present on the land, or that potentially could be established, should be one of the first steps in setting up an intensive forest management plan. Foresters need site productivity information so that they can concentrate intensive management on the most productive forest lands. Armed with site and yield information, a forest manager can estimate future wood supplies, profits , land acquisition and industrial investment.

There are two main steps to follow in forest site evaluation: (1) identify the most productive sites; and (2) determine the most productive and valuable tree species for each of these sites. Generally,the two steps are based on forest site index, the most frequently used indicator of site productivity in North America (Carmean, 1975). Different levels of productivity for the same species (step #1) can be estimated using site-index curves. Then site-index comparisons (step #2) can be made among several alternative tree species. Knowing site index for all alternative tree species enables a forest manager to select the most productive species to favour in managing mixed stands, or for programs such as tree planting and stand conversion. These two steps are complementary, and have a common goal--that of predicting and classifying land productivity for tree growth.

Site index estimates site quality directly in older forest stands and is a standard for developing indirect methods of site quality evaluation. Direct methods of estimating site index include: (1) site index curves; (2) site index comparisons between species; and (3) growth intercepts. Indirect methods of estimating site index include: (1) plant indicators; (2) physiographic site classification; (3) ecosystem classification; (4) synecological coordinates; (5) soil surveys; and (6) soil-site evaluation (Carmean, 1975; 1982).

Of all the methods for indirectly estimating site quality, soil-site methods have received the most emphasis in the United States (Carmean, 1975). In general, soil-site methods involve using features of soil, topography, and climate for estimating site quality. The most common approach is to determine the relationships between site index of a given tree species and specific features of soil, topography, and climate by means of multiple regression analysis. Many studies describing relationships between site quality and site features have been made in North America and Europe (Carmean, 1975; Hagglund, 1981).

Trembling aspen (*Populus tremuloides* Michx.) has an extremely wide range in North America, spanning 110 degree of longitude and 47 degrees of latitude (Fowells, 1965). It occurs in all the Canadian provinces, in the Lake States and Northeastern States, and in the western Mountains of the United States. The Canadian aspen resource is six to seven times as great as the aspen resource of the United States. The total *Populus* resource, which was evaluated in 1986, was estimated to total 3.2 billion m^3 (113 billion ft^3) (Poplar Counc. Can. 1988). *Populus* species account for about 11% of the total forest inventory of Canada and over 50% of the total hardwood inventory (Poplar Counc. Can. 1988).

Aspen utilization has expanded in recent years in both the United States and Canada. In Canada, commercial quantities of aspen are found in British Columbia, the three Prairie provinces, Ontario and Quebec (Jarvis, 1968). Sound aspen has a ready market for a variety of products including pulp and paper, fiberboard, plywood, particleboard, lumber and veneer (Maini and Cayford, 1968; Neilson and McBride,1974; USDA, 1976; Heeney *et al.*, 1980; DeByle and Winokur, 1985; Wong and Szabo, 1987; Ondro, 1989). In Ontario harvesting of aspen increased about 75 percent over the last ten years (O.M.N.R. 1976, 1986). In terms of gross total volume and landbase coverage, the poplar working group represents the second largest working group in the Boreal Forest and Great Lakes-St. Lawrence Forest Regions in Ontario (O.M.N.R., 1986; O.M.N.R.,1988).

The quantity and quality of aspen yield is closely related to forest site quality. On good sites aspen grows rapidly and can produce large yields of high quality products. For good sites converting to conifers and controlling aspen regeneration requires expensive and repeated silvicultural treatments that may not be economically justified. Thus good sites already stocked with aspen should probably be managed for aspen. In contrast, aspen grows slowly on poor sites, only small yields of poor quality fiber are produced, and disease may result in early stand breakup. Conversion to conifers may be justified for these poor sites because aspen is less vigorous and more easily controlled. Accordingly, there is a need for site quality studies for aspen so that forest managers in Northwestern Ontario can identify prime sites where managed aspen can produce large yields of quality products. Such site quality studies will help in decisions about what sites should be managed for aspen, and what sites should be converted and managed for conifers.

Forest land classification using FEC (Forest Ecosystem Classification) soil and vegetal types has now become an established basis for forest management interpretations in Northwestern Ontario (Sims *et al.,* 1990). This site study for aspen will relate FEC soil types identified on each plot to measured aspen site index. Thus we will be able to determine how closely FEC soil types are related to site index for aspen. Such information can be used for refining and interpreting forest land classifications based on the FEC system.

The soil-site method has been widely used in other areas to predict site index based on soil, topographic and climatic features. Accordingly, the goal of this study is to determine relationships between the site index of trembling aspen and features of soil and topography, using multivariate statistical analyses. Results of the analyses can be used for estimating site quality of forest lands where stands and trees are not suitable for directly estimating site index of trembling aspen.

This soil-site study for aspen will provide quantitative means for estimating site quality for trembling aspen in Northwestern Ontario. Soil keys based on multiple regression equations developed from this study will provide a means for identifying prime forest lands that should be managed for trembling aspen. This study also will provide a means for identifying poor sites for aspen where forest management might involve maintenance or conversion to conifer species. These results also will provide a foundation and a link between Forest Ecosystem Classification in Northwestern Ontario and the " Prime Site Management" strategy for Ontario (O.M.N.R., 1985).

LITERATURE REVIEW

FOREST SITE QUALITY

Forest site quality is a measure of the ability of forest land to grow trees (Carmean, 1975). Thus evaluating site quality corresponds to land capability estimation for various agricultural crops. The sum total of all environmental factors: genetic, climatic, biotic, and edaphic affect the capacity of the site to grow trees (Spurr and Barnes, 1980). In terms of timber management, site quality can be defined as "the timber production potential of a site for a particular species or forest type" (Clutter *et al.* , 1983).

HISTORY OF FOREST SITE-QUALITY EVALUATION

The need for standard methods of site-quality classification in North America became apparent in the early 1900's (Carmean, 1975). Three European schools of thought were considered for forest site-quality classification: (a) those influenced by Hartig (1795) and Cajander (1926), favoured a system of " forest site-types " (Zon, 1913); (b) those advocating the use of volume, as accepted earlier in Germany (Bates, 1918); and (c) those favouring site classification on the basis of height growth (Roth, 1916; 1918). The main supporters for height growth were Frothingham (1918, 1921a, 1921b) , Sterrett (1921) and Watson (1917). They all recognized volume as a desirable standard of site classification, but effects of species mixture and stocking made volume difficult to use for classifying site quality in natural forest stands. Supporters of height growth for site- quality evaluation state that: (1) height is a sensitive measure of differences in site; (2) height is independent of stocking and species mixture within broad limits; and (3) height-age relationships of trees are simple and easily determined in the field.

In 1923 a Society of American Foresters committee concluded that volume was the most accurate measure of site quality, and recommended the construction of normal yield tables, but did not recommend one site-quality evaluation method over another (Sparhawk *et al.*, 1923; Carmean, 1975). The failure of the committee to recommend a standard site-quality measure and the ease of use of site index based on height growth of the dominant and/or dominant and codominant trees in a stand has led to this measure being the most widely accepted and most commonly used measure of site quality in the United States (Carmean,1975; Pritchett and Fisher, 1987). Site index also is the accepted standard for estimating site quality in most European countries(Hagglund, 1981).

Site index is defined by the Society of American Foresters as "a particular measure of site class, based on the height of the dominant trees in a stand at an arbitrarily chosen age " (Ford-Robertson, 1971). Fifty years is most often used as the index age in eastern North America, except in the southern U. S. where the base age for pine plantations is usually 25 years. On the west coast of the U. S. and Canada, the base age is often 100 years for old growth conifer species (Carmean *et al.*, 1989).

Forest site-quality evaluation research and development has been widely conducted in North America. Coile (1952) reviewed the literature before 1952, and Carmean (1975) provided a comprehensive review of site-quality evaluation work in the United States. Ralston (1964) reviewed the literature from the period of 1954 to 1964. Graney (1977) reviewed site-quality relationships of the oak-hickory forest type in the United States. Hagglund (1981) reviewed literature on site quality published after 1973. Carmean (1982) reviewed site-quality relationships for conifers in the Upper Great Lakes area of the United States and Canada.

Additional reviews and evaluations of various methods of forest site-quality estimation are given by Coile (1948), Rennie (1963), Jones (1969), Shrivastava and Ulrich (1976), Pritchett and Fisher (1987), and Spurr and Barnes (1980).

FOREST SITE-QUALITY EVALUATION METHODS

All methods for estimating site quality can be divided into two groups : direct estimation of site index from trees and indirect estimation of site index using vegetal or environmental features (Carmean, 1975).

Direct Estimation of Site Index

Direct estimation of site index includes site-index curves, site-index comparisons between species, and growth intercepts.

Site-Index Curves

Estimates of site index are most often obtained using measurements of height and age with a height-over-age growth curve to estimate height at a standard age (Spurr and Barnes, 1980). These height-over-age growth curves are commonly referred to as site-index curves. Forest tree species that occur in even-aged, fully stocked stands, not disturbed by past cutting, severe fires, or heavy grazing are suitable for using site-index curves. Site-index curves are used for site-quality classification and for predicting the future height of trees (Strand, 1964). Thus, when suitable trees and accurate site-index curves are available, directly measuring site index is a convenient way for estimating site quality.

Early site-index curves were based on total height and total age data from yield plots that were averaged to create a guiding curve. This curve was then used to construct a set of proportional curves for a range of site-index levels. Graphical methods or least squares regression methods were used for constructing a set of proportional curves that had the same shape regardless of site-index level. These "harmonized" site-index curves were often inaccurate because they were derived sometimes from data that did not adequately represent the height-growth patterns of the species on varying levels of site index. Also the harmonized curves were unable to show changes in height-growth patterns for different level of site index because the guiding curves were based on averaged data. In an effort to develop more accurate and useful curves, foresters have developed "polymorphic" site index curves. These newer curves are based on data from stem analysis, and individual curves are derived for each level of site index using nonlinear regression models (Carmean *et al.* 1989).

Thrower (1986) developed site-index curves based on both total age and on breast-height age. He found that site-index curves based on breast height were more precise in predicting site index for both white spruce (*Picea glauca* (Moench) A. Voss) and red pine (*Pinus resinosa* Ait). Thrower showed that increased precision for breast-height age curves was due to the elimination of slow and erratic juvenile height growth before trees reach breast height.

Site-index estimates for a particular tree species are often related to growth and yield tables for different stand areas and levels of site index. In this way, site index is used as an intermediate step towards the goal of predicting the capability of forest land to produce wood (Carmean, 1975).

Site-index curves for trembling aspen in North Central Ontario were developed by Deschamps (1991). Stem analyses data were taken from dominant and codominant trembling aspen trees growing in 89 site plots. These stem analyses data were used to compute height-growth curves, polymorphic site-index curves, and site-prediction equations for trembling aspen based on breast-height age.

Site-Index Comparisons

Site-index comparison is a direct method of site-evaluation based on determining site-index relations among two or more species on the same site (Carmean, 1975). Many stands suitable for site-index measurements may not contain the tree species for which site estimates are desired. For such stands we can use the tree species actually present for estimating site index. Then species comparison graphs and equations can be used to convert the site index of the species present to the site index of the desired species. These graphs and equations are based on research that quantitatively expresses site-index relationships between the many alternative tree species that can occur on a particular area of land. Thus site index can be estimated based on measuring site index using the species present in the stand and then using equations or graphs that predict site indices of other alternative species. This method permits a quick and easy way of extending direct site-index estimation to other areas where the forest manager has the problem of selecting the most productive species among many alternative species to favour in forest land management. (Carmean,1972, 1975, 1979, 1986; Coile, 1948; Copeland, 1956; Curtis, 1962; Doolittle, 1958; Harrington, 1987; Olson and Della-Bianca, 1959).

Growth Intercepts

Growth intercepts are another direct method of estimating site index which has most often been used with coniferous species having easily recognized nodes marking annual height growth (Carmean, 1975). Site-index curves use tree height growth to a specified base age (usually 50 years) for developing height-growth curves. In contrast, the growth-intercept method uses only a selected period of early height growth rather than long term height growth portrayed by site-index curves (Carmean, 1975; 1982). The total length of the first three to five internodes produced after trees reach breast height is often used as an index of site quality. However, Thrower (1986, 1987) found that growth intercepts for both white spruce and red pine were more precise when internode measurements were started somewhat higher than breast height. Thrower found that the best precision in estimating site index resulted from using the average length of three to five internodes above 2.0 m for white spruce, and above 1.5 m for red pine. The growth intercept method can be used only in young plantations and natural stands of tree species having well defined whorls marking annual height growth (Alban, 1972; Carmean, 1975; Thrower, 1987).

Indirect Estimation of Site Index

Many areas lack suitable trees for direct measurement of site index. Such areas include cutovers, burned areas, stands that have been repeatedly high graded, very young stands, unevenaged stands and agricultural and other non-forested lands. For such areas indirect measures of site index are particularly useful. Indirect estimation of site index involves determining the relationships between site index and measurable soil, topographic climatic or vegetal characteristics of the site. Indirect estimations of site index can be made using plant indicators, physiographic site classifications, soil surveys, ecosystem classifications, and soil-site evaluation. The soil-site method, a more fruitful method of indirectly estimating site index, has received major attention in recent years (Carmean, 1975).

Plant Indicators

The concept of using plant indicators for classifying lands originated in Europe more than two centuries ago. The first attempts at using plant indicators to determine productivity were subjective apprasials based on tree appearance carried out by Hartig (1795). Cajander (1926) linked plant cover with site productivity in Finland and Russia at the turn of the 20th century. The system which Cajander developed divided the country into five vegetal classes based on plant communities. These vegetal classes were then divided into site types using species of understory plants (plant indicators) that were consistently found under a narrow range of site conditions. Characteristics that have been related to site index have been the presence, abundance, constancy of occurrence, and size of understory plants (Carmean, 1975).

Physiographic Site Classification

Physiographic features have been used to subdivide forest regions into areas with similar climate, moisture, and nutrient status (Carmean, 1975). This method is based on a " holistic" concept of site which integrates the complex of land and forest features within particular regions. Hills " total site" classification for Ontario is such a system (Hills, 1952; 1960). An important distinction is that Hill's site classification system is a method for landscape classification, thus cannot be considered as a method for site quality estimation.

Ecosystem Classification

Ecosystem land classification attempts to break complex forest landscapes into progressively more homogeneous units having similar vegetation, soil and topographic conditions. There are many different approaches to forest ecosystem land classification including the efforts of Krajina (1965) in British Columbia, Corns and Annas (1986) in Alberta, Hills (1952), Rowe (1972), Jones *et al.* (1983), Nicks (1985), Greenwood (1987) and Sims *et al.* (1990) in Ontario. The Forest Ecological Classification (FEC) system developed for the Northwestern Region of Ontario uses both soil characteristics and plant communities as a basis for developing a classification system for use in forest management. Presently this system divides soils into a shallow to bedrock (less than

100 cm) group, and a deep to bedrock or boulder pavement (deeper than 100 cm) group. The deeper sites are then subdivided into 13 groups based on moisture, texture, depth of organic layers, and presence of gleying and mottles. The shallow sites are divided into nine soil groups based on texture and the thickness of the mineral or organic horizons. Vegetation is divided into 38 types based on the overstory species, i.e. 11 hardwood types, 9 mixedwood types, and 18 softwood types (Sims *et al.,* 1990). Efforts are now being made to relate these FEC soil types to site quality for various forest tree species.

Soil Surveys

Soil surveys have been used as a basis for estimating site quality in some forest regions (Carmean, 1975). In the United States and in Canada, agricultural lands have been given highest priority for soil surveys while forest lands have received less attention. More recently soil surveys have been conducted on forest lands. Soil surveys are very valuable for land use planning in that they provide a comprehensive survey of land capability for many purposes including agriculture, forestry, recreation and wildlife.

Many studies show that soil series often have wide site-index ranges. Thus, for many areas the range of site index is too wide for dependable forestry use. Reasons for such wide site-index variation are that many soil series include wide ranges of soil and topographic features that are important for tree growth. As a result soil surveys based on such broad and variable soil series cannot accurately classify units of land of varying site quality (Carmean, 1961; Pawluk and Arneman, 1961; Farnsworth and Leaf, 1963; Shetron, 1969, 1972; Watt and Newhouse, 1973). Carmean (1975) cites other possible deficiencies such as biased sampling based on " model" soil profiles, and the lack of statistical analysis techniques to establish soil-site index relationships.

Soil-site Evaluation

The soil-site method of site-quality evaluation involves estimating site index based on various soil, topographic and climatic features. The most common approach involves correlating site index estimated from many site plots with associated features of soil, topography and climate using multiple regression analysis (Carmean, 1975; Prichett and Fisher,1987).

Soil-site methods have received more emphasis in North America than other methods for indirectly estimating site quality. Since the early decades of this century, numerous studies have been made on the relationship between various soil properties or profile characteristics and the rate of growth or site index of forest stands (Carmean, 1975; Pritchett and Fisher, 1987). One of the first soil-site studies in North America was conducted by Haig (1929) who related site quality on 95 plots established in 26 red pine plantations in Connecticut to the "colloidal" content of the various soil horizons. He found that site index of red pine increased as the percentage of the finer fractions (silt plus clay) increased in the A horizon; the single most significant variable in his study was the total nitrogen content of the A horizon.

Another early soil-site study was made in Connecticut by Hicock *et al.* (1931). This study involved red pine plantations from 12 to 30 years of age, occurring on a wide range of soil types. They found that site index was poorly correlated with soil series and with individual soil attributes such as texture, and character of the A horizon and the subsoil.

Auten (1935) studied physical and chemical soil properties associated with the growth of 135 black locust plantations and 120 black walnut (*Juglans nigra* L.) plantations. He concluded that the physical properties of the subsoil were most influential in determining site index. Plasticity, compactness, and structure of the subsoil gave the highest correlations with site index.

Hall (1935) pointed out the advantages of favouring pitch pine on the sandy soil of Cape Cod because of its resistance to gypsy moth defoliation as compared to other species. Moreover, pitch pine was found to grow faster on the light sandy soils than Scotch pine (*Pinus sylvestris* L.).

Turner (1938) studied second growth shortleaf and lobolly pine in Arkansas. He concluded that site index of these species was most closely associated with soil texture, depth to the B horizon, and slope steepness.

Lunt (1939) studied the relation between certain chemical characteristics of the surface soil and the site index of even-aged stands of oak in Connecticut. Essentially no correlation was discovered between oak site index and various soil characteristics associated with fertility. At the same time, Lunt concluded that there was a relationship between site index and topography, the best sites being on lower slopes.

Heiberg (1941) observed a marked growth response of red pine (*Pinus resinosa* Ait.) and white pine (*Pinus strobus* L.) to surface applications of organic matter in the Adirondacks of New York. As well as increasing water-holding capacity, it is evident that the organic matter supplied some significant fertility because the response occurred the first year after application of green slash.

Coile (1952) and his students conducted most of their soil-site work in the southern pine region of the United States from the middle 1930's to the 1950's. Coile placed much emphasis on the importance of physical soil properties in determining site quality. He considered that available moisture is the most important factor determining site quality and that aeration and rooting space greatly influence water availablity.

Coile (1948) recognized that site index was also affected by chemical soil properties. However, he felt that nutrient deficiencies were usually not as limiting as physical properties and that nutrient deficiencies would usually be reflected in various physical properties. He also realized that physical soil factors and topography are more easily recognized in the field than are chemical soil factors. Thus many early soil-site studies did not consider chemical soil properties, but focused largely on physical soil properties.

Lutz and Chandler (1946) as well as others did not agree with the idea that physical soil factors were all important. Several studies have indicated the importance of certain nutrients as factors influencing site index. For example, Voigt *et al.,* (1957) found that northern Minnesota soils with high levels of calcium, potassium, and nitrogen are more productive than soils with low levels of these nutrients. Many of the more recent soil-site studies have considered the effects of soil chemical properties on site quality.

Hills (1952) separated Ontario into site regions based partially on similar climate and geologic conditions. The trend in most soil-site studies has been to select study areas that are in a region of relatively similar climate thus eliminating the effects that large changes in climate might have on site quality. Despite the trend of selecting study areas of similar regional climate, some studies have found that local changes in elevation, topography, wind patterns, cold air drainage, or transitional zones in climate are related to site quality. McClurkin (1963) found that the amount of rainfall from January to June was the most important variable affecting longleaf pine (*Pinus palustris* Mill.) growth rate in a region extending from Mississippi to Texas. Carmean (1954) found that site index of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) was related to annual precipitation and elevation.

Carmean (1964, 1965, 1967) expressed the relationships between soil features and black oak (*Quercus velutina* Lam.) site indices in southeastern Ohio in terms of the depths of different soil horizons and the amount of stone, sand or clay in the horizons. In addition, aspect, slope length and distance to ridgetop were included in one equation.

Fralish and Loucks (1975) studied the effect on precision of adding variables like soil nutrients (Mg, Ca, K, P) to equations that originally comprised only variables measurable in the field. However, they found that nutrient values only slightly increased precision in estimated site index for trembling aspen, probably because of the strong relationship between aspen growth and the amount of available water. Coile (1948) also pointed out that physical and chemical soil factors often are closely associated, thus equations based on physical soil factors also could express effects of chemical factors on site quality.

Soil-site studies have become quite diverse using soil profile features, physical and chemical variables, topography, climate, and plant indicator species. Reviews on soil-site studies have been made by Coile (1948, 1952), Doolittle (1963), Rennie (1963), Ralston (1964), Shrivastava and Ulrich (1976), Carmean (1975, 1982) and Hagglund (1981).

Carmean (1975) listed 793 publications dealing with forest site quality in the United States. He divided the past work from the 1930's to the 1970's in the United States into five parts: (1) soil-site studies for southern pines; (2) for northern conifers; (3) for eastern oaks; (4) for eastern hardwoods; and (5) for western conifers. He concluded from those studies that the most common features related to site quality are surface soil depth, subsoil texture, aspect, and slope position.

SITE FACTORS RELATED TO TREMBLING ASPEN SITE QUALITY

Climate

Trembling aspen occurs over a wide range of climatic conditions. The key climatic gradients that may affect the range and growth of aspen are temperature and moisture (O.M.N.R.,1988). Within the range of trembling aspen in Canada, climatic factors vary as much as 5^{o} to 23^{o} C for mean daily July temperature, 13 to 445 cm for mean annual precipitation, and 40 to 260 from growing degree days above 5.6^{o} C (Maini, 1968a).

Within the commercial range of trembling aspen in Canada and the United States, climatic parameters vary as follows: 16^{o} C to 19^{o} C for mean July temperature; 635 mm to 864 mm for mean annual precipitation; and 80 to 130 days for the mean frost-free period (Chapman and Thomas, 1968).

Within the major commercial range of trembling aspen in Ontario, the mean annual growing season varies between 150 and 170 days, the mean daily temperature in July from 18^{o} C to 22^{o} C and the mean annual precipitation from 500 mm in the west to over 800 mm in eastern locations (Anon, 1957).

The climate range of the Boreal Mixedwood forest section is important for aspen production (Corns, 1988). The Boreal Mixedwood lies within the Boreal Climate Region of Hare and Thomas (1974). The Mixedwood forest has a low-energy climate with short winter and long summer days. Climate is continental with more than half of the total precipitation occurring as summer rain (Strong and Leggatt, 1981). In Alberta, the

Boreal Mixedwood has a mean annual temperature of 0.5° C, 970 to1,310 growing degrees for days above 5° C, a mean frost-free period of 85 days, mean total precipitation of 300 mm and a moisture deficit of 190 mm (Strong and Leggatt, 1981). Climate in Saskatchewan is similar (Kabzems *et al.*, 1986) except that average annual precipitation is about 400 mm (Corns, 1988).

Soils

Trembling aspen occurs on a wide variety of soils, from wet clays to dry sands and peat (Kittredge and Gevorkiantz, 1929; Kirby *et al.*, 1957; Steneker, 1976; Fowells, 1965). However, only a limited range of soil types produces aspen of suitable quality and quantity for commercial production. The soils best suited for aspen production result from a combination of three interrelated soil attributes: texture, moisture, and nutrients (O.M.N.R., 1988).

Soil Texture

Soil texture is the most important single factor affecting the site class of aspen soils (Fralish, 1972; Sutton, 1958). The silt and clay content of soil affects both the moisture regime and soil fertility level (Heeney *et al.* 1980). Many studies have reported relationships between trembling aspen growth and soil texture.

One of the earliest opinions on the soil requirements of aspen was expressed by Baker in 1925. He found that aspen grows in practically every variety of soil found in the climatic belt to which it is suited, from loamy sands to heavy clays. But the development of stands varies considerably on different soils. The chief direct influencing factor is rockiness of the soil. The best aspen development is on rich soils found on deep flats supplied with plentiful moisture (Baker, 1925).

Kittredge and Gevorkiantz (1929) found that loams and silt loams are excellent sites for aspen growth. They reported that the medium to coarse sandy soils of outwash plains or sandy moraines usually have site indices below 16.8 m (55 feet). The fine sandy soils of outwash plains, the clay and clay loam soils, and the shallow sandy loam soils on rock outcrops belong also to site index classes less than 16.8 m (55 feet). Good sites above 20.4 m (67 feet) include silt loam soils on boulder clay, clayey moraines, the heavier soils of old lake beds, soils not too shallowly underlain by bedrock, and fine sandy soils on boulder clay.

Westveld (1933) reported that the best sites for trembling aspen occurred on loams and sandy loams with a sandy clay till or drift substratum at 63.5 cm-76.2 cm (25 to 30 inches), or on silt loams and loams with either clayey subsoils or open coarse sand, gravel, or cobbles below 101.6 cm (40 inches). The poorest sites were shallow sandy loams resting on bedrock.

Roe (1934) reported that in the Lake States sandy, rocky, or excessively drained soils are poor aspen sites, while the best sites tend to be on loams with a heavy subsoil and moderately high watertable.

Kittredge (1938) studied trembling aspen in the Lake States and found a correlation between aspen site index and the texture of the upper 20.3 cm (8 inches) of soil. However, differences in site index within texture classes were often greater than the differences between successive texture classes, and he concluded that other factors had to be considered.

Stoeckeler (1948, 1960) also studied trembling aspen site quality in the Lake States and found that trembling aspen site index increased with an increase in silt plus clay content up to a certain point. On sands (15 percent or less silt plus clay) growth is reduced because of droughtiness combined with a generally low nutrient level. The optimum soil for trembling aspen is a loam with a silt plus clay content around 50 to 55 percent. For very heavy-textured soils, especially tight clays, Stoeckeler found lower site indices. This is attributed to poor aeration and too wide a fluctuation in moisture. The best sites are in the range of good sandy loams to silt loams. The intermediate group consists of light sandy loams. The fine sands, loamy sands, and coarse sands are definitely inferior.

Barth (1942) sums up the soil requirements of European aspen (*Populus tremula* L.) in Norway as follows: "Aspen demands a light, loose, organic, and preferably lime containing soil of a fresh and moist nature, as characterized by the grass and herb-rich forest type. On dry, poor soil aspen does not develop well. Nor does aspen like hard, heavy, or clay soils. It resents poorly drained soils as much as other tree species. On the other hand, it thrives well on wet soils where the ground water is in steady motion".

Einspahr and Benson (1967) found that percent clay and the exchangeable bases that were correlated with percent clay were the soil factors that apparently had the most influence on tree growth.

A better correlation was obtained by Stoeckeler (1960) between site index and the texture of the A and B horizons. He found growth of aspen was optimum on loams to silt loams having about 60 percent content of silt plus clay and with at least reasonably good internal drainage. Poorest growth was found on sands with less than 15 percent silt plus clay or on soils with deep, coarse, gravelly subsoils.

Meyer (1956) divided 36 aspen plots in northern Minnesota into three groups on the basis of soil texture and acidity: poor, site index less than 18.6 m (61 feet); medium, site index 18.6 - 21.3 m (61 to 70 feet); good, site index more than 21.3 m (70 feet).

Among soil properties measured so far, most studies agree with

Stoeckeler 's (1960) conclusion that trembling aspen achieves its best production on loamy soils with a moderate silt plus clay content (O.M.N.R., 1988).

Soil Moisture

Soil moisture availability is affected by soil texture, soil organic matter, soil porosity, depth to water table, and drainage (O.M.N.R., 1988). Increased available soil moisture results in better tree growth, thus better site quality. However, excessive soil moisture results in poor soil aeration, and thus poorer growth and poorer site quality. Soil moisture content is the result of many soil, climatic, and vegetal characteristics including precipitation, relative humidity, evaporation, and the presence of vegetation affecting the amount of soil moisture used in transpiration. Overland flow and seepage affects losses or gains of soil moisture. Topography, soil texture, soil structure, and organic matter content are related to the rate of water infiltration and the moisture holding capacity of water held in the soil (Pritchett and Fisher, 1987).

Trembling aspen is found growing on a wide range of soil moisture regimes. Aspen occurs on all moisture regimes except the extremely dry "0" and the extremely wet sites "9" (Heeney *et al.*,1980). However, trembling aspen is sensitive to water deficits (Sucoff, 1982) because of the relatively poor stomatal control of the aspens (O.M.N.R., 1988).

Perala and Laidly (1989) found that young aspen stands respond to thinning and fertilization. Thinning resulted in a marked increased basal area, diameter, volume and height growth. Nitrogen-fertilization also resulted in increased growth but the magnitude was less than for thinning. They considered that improved growth resulted from water conservation related to density control.

Fralish and Loucks (1975) used multiple linear regression to show that aspen growth (site index) in north central Wisconsin is strongly related to the amount of water available for growth. They also showed that available water, in turn, is dependent on water-holding capacity of the soil, depth to water table, and rate of water usage as influenced by exposure. Any factor which tends to reduce the amount of available water may have an adverse effect on aspen development. Such factors include reduced silt and clay content, increased rock content, higher summer temperatures because of locale, exposure to wind, and site drainage. The effects of aspect, stand slope position, and nutrients on site index in north central Wisconsin appear overshadowed by exposure, water-table depth, and available soil water.

Strothman (1960) found that depth to water table was an important factor in soils having less than 30 percent silt plus clay content. A depth to water table of less than 152 cm improved site quality. On clay soils, a water table within 61 cm of the soil surface reduced site quality (Strothman, 1960). Poor drainage, indicated by mottling in the upper 30 cm of soil, reduced site index compared to a similar well drained soil (Stoeckeler 1960).

In the Lake States, good aspen sites have a water table between 0.91 to 1.83 m (3 to 6 feet) below the soil surface (Stoeckeler, 1960; Fralish, 1972). Sandy soils with less than 15 per cent silt plus clay were found to be poor for trembling aspen because of a lack of moisture (Stoeckeler, 1948). Best growth occurs on well drained soils with a constant supply of moisture (moisture regimes 2 and 3) (O.M.N.R.,1988).

Moisture stress may be the most critical factor controlling aspen longevity (Shields and Bockheim, 1981). In the southern portions of its commercial range,where warm temperatures increase evapotranspiration, aspen development is limited by soil moisture availability (Maini, 1968b).

Steneker (1976) illustrated good, intermediate and poor sites on a matrix of soil texture and soil moisture to indicate conditions for good, medium, and poor trembling aspen sites.

Recent research in northern Wisconsin has shown that soil texture and water holding capacity are critical factors in maintaining aspen. As the percentage of silt and clay increases, average site index increases. A water table within the rooting zone will increase aspen growth; water tables deeper than 2.44 m (8 feet) have little effect on growth; water tables less than 0.61 m (2 feet) from the surface will decrease growth (Adams and Gephart, 1989).

Heeney *et al.* (1980) showed generalized relationships between aspen site classes and soil characteristics, which served as silvicultural guidelines in Ontario. The best aspen sites (site class 1) have been found on very fresh sites (moisture regime 3) on well-structured clay and silt loam; these fresh clay soils usually have an accumulation of humus of less than 10.2 cm (4 inches). Good aspen sites (site class 2) occur on many fresh sites (moisture regimes 2 and 3); these may be clays and silt loams, deep fine sands, deep loamy sands and sandy loams. The poorest aspen sites (site class 3) occur on the drier soils (moisture regimes 0 and 1), including medium and coarse sands, shallow loamy sands and sandy loams over bed rock; poor sites also occur on the moist clays (moisture regimes 4 and 5) where there is a lack of aeration.

Soil Nutrition

Aspen grows on soils having a wide range of fertility. Those soils which have free lime, or have an otherwise high content of calcium, seem to produce the best aspen (Heeney *et al.*, 1980). The fact that aspen has high calcium requirements (Alban *et al.*, 1978; Shields and Bockheim, 1981) supports Stoeckeler's (1960) hypothesis that the longer lifespan of aspen in northern Minnesota is due to abundant calcium in the subsoil.

In general, aspen rapidly accumulates large quantities of nutrients and stores them in woody tissues, particularly bole bark and bole wood. Nutrients that are returned in leaf litter are released relatively rapidly during decay (Pastor, 1989).

High levels of available nutrients, particularly calcium, are favourable for aspen growth (Zehngraff, 1947). Meyer (1956) found that 85 percent of the best sites were underlain with calcareous parent material, compared to 45 and 25 percent of the medium and poor sites, respectively. As Stoeckeler (1960) points out, soil nutrient status and the percent silt plus clay content are related, because fine textured soils normally have a higher cation exchange capacity than coarse textured sandy soils.

Stoeckeler (1948) reported that excellent aspen sites occurred on soils developed from a gray glacial drift, rich in lime. Here aspen may attain diameters of 45.7 cm to 61 cm (18 to 24 inches) and heights of 27.4 m to 30.5 m (90 to 100 feet). The stands may attain an age of 60 to 75 years and still be reasonably free of heart rot. Abundant calcium and probably other nutrients in these soils evidently contribute to the greater longevity and soundness of the aspen. From studies in Wisconsin and in Ontario, it appears that some soils with slightly acid subsoils but devoid of free carbonates may still have enough calcium to meet the optimum needs and may approach or equal the yields indicated for the good sites described by Stoeckeler.

Voigt *et al.* (1957) found that the average annual growth of aspen on soils with high levels of calcium, magnesium, potassium, and nitragen was over 4 times greater than the average annual growth on soils having a lower base status and nitrogen content. Analyses of foliar samples and aspen litter showed a close relationship between the supply of exchangeable bases in the soil, where aspen were growing, and the level of calcium, magnesium, and potassium in the tissues of trembling aspen. Good sites having large volumes of wood per unit of land were restricted to soils having large amounts of total nitrogen and exchangeable nutrients. Voigt also found that trees more than 60 years of age were found only on soil whose Ao horizons had more than 25 me. of exchangeable bases per 100 g of soil. The life span of merchantable trembling aspen on poorer soils in the region studied appears to be limited to 50 years or less.

Excellent reviews of aspen ecology, management and utilization include Graham *et al.*, (1963), Maini and Cayford (1968), USDA Forest Service (1972), Neilson and McBride (1974) , DeByle and Winokur (1985), and Corns (1988).

THE COMMON CHARACTERASTICS OF TREMBLING ASPEN

Regeneration and Development

Trembling aspen is a relatively short-lived, fast-growing tree. It is dioecious; that is, male and female flowers are separate and are borne on different trees (Steneker, 1976). In the Lake States, aspen usually flowers in April and leaves appear in May (Adams and Gephart, 1989). Best seed germination and survival is on alluvial or humus seedbeds having moderate temperatures, good drainage, and little competition from other vegetation (Steneker, 1976; McDonough, 1985).

Trembling aspen begins producing seed at about 20 years of age with good seed crops every 4 or 5 years thereafter (Fowells, 1965). However, aspen regeneration by seed in the field is uncommon (Maini, 1968b; Brinkman and Roe, 1975) because seed loses viability quickly after maturing and requires a moist seedbed for germination (Steneker, 1976).

The common method of aspen reproduction is through suckers, which develop from pre-existing primordia on lateral roots located below the soil surface (Schier, 1973). Suckering occurs after trees are cut or killed by fire thus apical dominance is broken resulting in changed hormonal balance (ratio of auxins and cytokinins) in the roots (Navratil and Bella, 1988). Once apical dominance is broken, soil temperature, carbohydrate reserve and clone genetics are the key factors in controlling the density of sucker development (Garrett and Zahner, 1964; Maini and Horton, 1966; Steneker and Walters, 1971; Zasada and Schier 1973; Steneker, 1976: Navratil and Bella, 1988).

The optimum temperature range for suckering is 20^{o} to 30^{o} C. The amount of suckering depends on the degree of stand disturbance (number of overstory trees cut or burned and amount of ground vegetation removed) and the inherent ability of the trees to sucker (Steneker, 1976).

Suckers which develop from the root system of one parent tree are genetically identical and together are called a clone. All trees within a clone will show identical bark and leaf characteristics, stem form, and incidence or lack of decay. Many suckers within a clone, particularly at an early age, will have interconnected roots (Steneker, 1976).

Wide clonal variations in suckering capacity, growth rates and disease susceptibility, show that natural aspen stands are genetically and ecologically very diverse (Barnes, 1969; 1975). Aspen requires maximum sunlight for best growth. Repeated vegetative reproduction of aspen results in the formation of clonal stands; each may contain from a few to several hundred trees and may be spread over areas as large as 1.6 ha (4 acres) in size. A fully stocked aspen stand when clearcut or burned may produce 160,000 suckers per ha (40,000/ac), but mortality is high and by 30 years of age these numbers are reduced to 4,000 to 8,000 per ha (1,000-2,000/ac) stems and at age 40 stocking averages 1,200-1,600 trees per ha (300 -400/ac) (Adams and Gephart, 1989).

Large areas of aspen forests will not be harvested in both the United States and Canada, and natural succession will change the composition of these stands. Where aspen is found on the cooler, wetter sites, succession will be towards balsam fir (*Abies balsamea* (L.) Mill) or white spruce. On the moist, fertile soils, succession will be towards climax hardwoods, such as sugar maple (*Acer saccharum* Marsh), basswood (*Tilia americana* L.), ironweed (*Vernonia schreb*) and red maple (*Acer rubrum* L.). Where aspen is mixed with paper birch (*Betula papyrifera* Marsh) and red pine or jack pine (*Pinus banksiana* Lamb.), the pine and birch can be expected to outlive it (Adams and Gephart,1989).

Growth and Yield

The earliest detailed study of growth and yield for trembling aspen in North America was reported by Kittredge and Gevorkiantz (1929). They considered the possibilities of aspen as a forest crop and prepared yield tables for five site classes. Site index was based on total height of dominants at a total age of 50 years. Site-index curves were given and yields are given for site classes 24.4 m, 21.3 m, 18.3 m, 15.2 m, and 12.2 m (80, 70, 60, 50 and 40 feet).

Johnson, Kittredge, and Schmitz (1930) found that the rate of growth varies with the soil and site conditions and with the age of the stand. For example, at 30 years, on a medium site (SI=19-21 m), well stocked stands have an annual growth rate of about 3.58 m^3 per ha, and at 50 years almost 8.06 m^3 per ha, after which the average annual growth rate diminishes. On a good site (SI=24 m) at 50 years, the annual growth rate may be as much as 11.2 m^3 per ha, in contrast to a poor site (SI=12 to 15 m) where annual growth is as little as 0.9 m^3 per ha.

Anderson (1936) reported the experience of a forest survey with aspen yields. Survey figures showed that typical volumes in natural aspen stands fell far below the yields predicted by the yield tables. Reasons given for such low yields were understocking, poorer form, large amounts of defect, and different utilization standards.

Zehngraff (1947) found that in pure stands on good sites the best trees will attain heights of 24.4 m (80 feet) and diameters of 38 cm (15 inches) at 60 years. Thomas (1968) reported that 40-year old dominant trembling aspen trees on dry sites had diameters at breast height of about 14 cm (5.5 inches), but on moist sites diameters were about 16 cm (6.3 inches). On dry sites diameters of dominant 50-year old trees were about 16.5 cm (6.5 inches) and about 19 cm (7.5 inches) on moist sites. While trees of such dimensions do not satisfy the large-log industry, they do produce substantial amounts of fiber at these ages.

Volumes of mature aspen stands on good sites (SI=24 m) are comparable to those of more desirable conifers such as white spruce and jack pine. In Saskatchewan, the gross volume of average stocked aspen stands at 100 years of age is reported by Kirby *et al* . (1957) to vary from about 210 m^3 per ha (3,000 ft^3 per acre) on poor sites to about 350 m^3 per ha (5,000 ft^3 per acre) on good sites. Data collected by Maclean and Bedell (1955) in the northern clay belt of Ontario indicate that empirical yield there is similar to that in Saskatchewan. Normal yield tables for aspen in northern Ontario (Plonski, 1974) show that volume varies from about 459 m^3 per ha on good sites to about 271 m^3 per ha on poor sites at 100 years.

Decay in Trembling Aspen

Decay commonly occurs in living trees of all poplar species resulting in reduced yields for pulpwood, veneer, and sawlogs (Peterson *et al.*, 1989). The relatively extensive stem decay in trembling aspen is one of the major reasons for its low degree of acceptance by forest industries (Basham, 1977). Although gross volumes of poplar stands compare favourably with those of most coniferous stands, merchantable volume is greatly reduced by decay (Riley, 1952).

Decay has a significant and retarding effect on past utilization of aspen, and will have a significant influence on future utilization (Jarvis, 1968). For example, Thomas (1968) stated that in Alberta the poplar-based industry will have to make greater use of small-sized logs, such as those from trees 50 years of age or younger, if the problem of decay is to be overcome.

Individual trees on good sites may reach an age in excess of 100 years. However, stands usually break up much earlier, due to extensive decay and loss in vigour. Heart rot in the trunk causes the most serious cull losses in aspen. *Fomes igniarius* , a white decay with characteristic black zone lines, is responsible for about 35 % of the decay in aspen. Fruiting bodies of the fungus are gray, hooflike conks with brown pore surfaces. Another serious rot is *Corticum polygonium*, a yellow brown stringy rot recognizable by small white crusts, often occurring on the underside of branch stubs. Decay establishes itself in the stem, primarily through dead branch stubs and stem wounds, even before age 20. However, actual volume loss in stands will not occur until later when stand breakup becomes pronounced on certain sites. By age 70 the amount of decay may average 25 % by volume and will increase rapidly thereafter. Decay losses tend to be more severe on poorer sites, primarily because of slower tree growth (Steneker, 1976).

The survey showed that trembling aspen trees yielding at least one log require 20 years on both moist and dry sites. At this age trembling aspen is likely to be 4 to 5% decayed (Thomas, 1968).

Basham (1977) also found that *Radulum casearium* seldom occurred in aspen younger than 60 years; *Peniophora polygonia* was by far the most frequently encountered Basidiomycete in the youngest trees sampled (roughly 35 years), but was seldom isolated from trees over 100 years old. *Fomes igniarius*, the major cause of stem decay in aspen, did little damage in trees younger than 60 years, but was frequently responsible for massive decay cylinders in trees 80 years and over. He suggested that it is advisable to harvest trembling aspen in Ontario well before it reaches 100 years of age.

METHODS

DATA COLLECTION

Data Sources

The data used for this study came from 98 aspen plots from the following two sources:

1). Data were collected by Deschamps in 1985 who established 89 plots for his graduate thesis (Deschamps,1991). He established circular plots (0.08 ha in size) in pure, even-aged aspen stands, and all trees within this area were measured for diameter at breast height (1.3 m); a map was drawn by Deschamps for each plot showing location. On each plot, 3 to 4 dominant and codominant aspen trees were selected for stem analysis. In 1989 and 1990, M. Roddick, a forester of the Ontario Ministry of Natural Resources, relocated most of Deschamp's plots and collected soils data. I visited some of Deschamps' site plots with Roddick in 1990 and made detailed soil descriptions and collected soil samples.

A total of 56 Deschamps plots having trees over 50 years of age were selected for use in this study.

2). An additional 42 older aspen plots, established between 1983 and 1987, were supplied by the Ontario Ministry of Natural Resources (MNR-FEC data). The O.M.N.R. plots were essentially in pure, even-aged aspen stands.

Study Area

These 98 sample plots are located within the O.M.N.R. Northwestern Region, that lies mostly in the Thunder Bay District and in small portions of the Nipigon and Ignace Districts (Figure 1). The area extends from approximately 48°30' to 50°15' N latitude and 88°15' to 91° W longitude.

In general, the climate of Northwestern Ontario is microthermal and humid (Sims *et al.*, 1990) according to the Thornthwaite system (Sanderson, 1948). Seasonal temperatures tend to increase with decreasing latitude and are further moderated in proximity to Lake Superior (Sims *et al.* ,1990). Most of the region lies within the 2 W, 3 W and 4 W physiographic site regions of Hills (1952), and the Boreal forest region of Canada according to Rowe (1972).

The geology, topography, and soils of the area have been described by the O.M.N.R. (Sims *et al.*, 1990). The area is underlain by mostly Archean (Precambrian) rocks of the Superior and Southern Provinces (Pye, 1969). In some areas, Phanerozoic sedimentary rocks overlie the bedrock. Glacial landform patterns are distinct due to complex events which occurred during glacial and early post-glacial periods (Zoltai, 1961, 1965, 1967). Common surficial deposites include shallow drift, undulating ablation and basal tills, morainal and drumlin features and large expanses of predominantly thin glacial sediments over rolling to rugged bedrock (Sado and Carswell, 1987). Glaciofluvial and glaciolacustrine deposites are also very common but tend to be more localized (Sims *et al.*, 1990).

Plot Location

Plots were located in fully stocked, even-aged pure aspen stands. The main stand selection criterion was the presence of dominant aspen trees that appeared to have been free-growing and uninjured (no evidence of

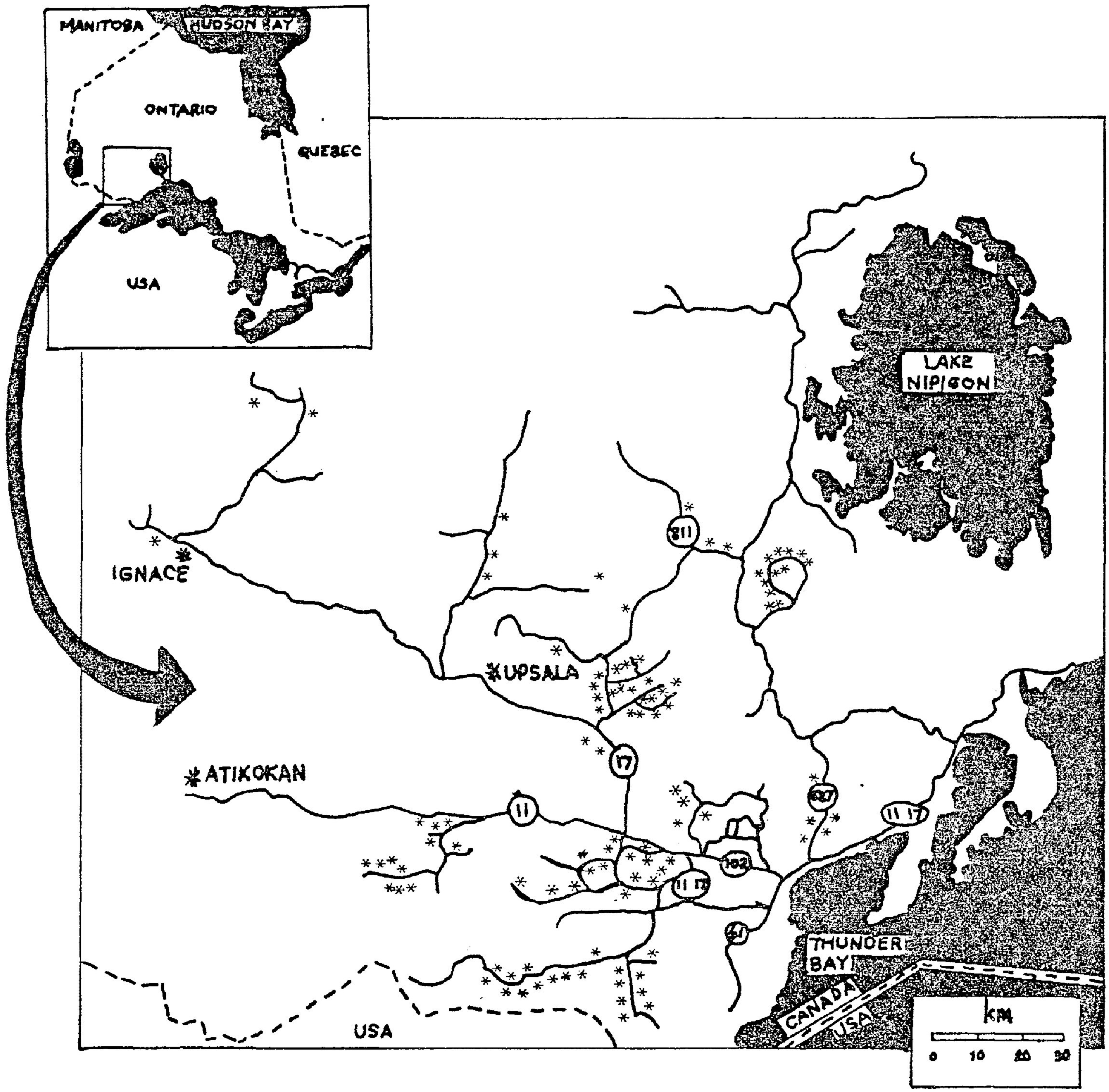


Figure 1. Location of trembling aspen soil-site study plots in Northwestern Ontario.

cutting or fire). All stands were at least 50 years in breast-height age. The range of high, medium, and low site quality (productivity) was sampled as well as the range of different kinds of soil, topography and geologic landform conditions where aspen stands occur. Each plot had a preliminary examination to observe if soil and topographic conditions were relatively similar within the plot.

Stem Analysis

Stem analyses were made on each plot using 3 to 4 dominant and codominant aspen trees that were well formed and showed no significant evidence of defect, deformity, or injury. These site trees were then felled, and limbed, and total height was measured using a 30 m tape. Discs were cut at the stump (0.1 m), 0.75 m., 1.3 m, and 2.0 m height; above 2.0 m discs were cut at 1.0 m intervals to 13 m, then at 0.5 m intervals to the tip of the tree. All discs were labelled by plot number, tree number, tree section number, then were bagged and transported to the Thunder Bay Forest Nursery and stored at 2^{o} C. Careful annual ring counts were made at each section point using magnification and illumination, and the computerized Tree Ring Increment Measuring (TRIM) system.

Site-Index Estimation

Height-age curves for each tree were plotted. The average age at each sectioning height was then calculated, and the adjusted height growth of the three or four dominant trees on each plot were averaged to obtain an average total age curve, and an average breast-height age curve. The average total age curve was based on years from suckering, and the average breast-height age curve was based on age from the first year above breast height. For each plot the height of the site trees 50 years after they reached breast height was read from the average height-growth curve. This height value for each plot was used as site index. Breast-height age was used rather than total age to avoid slow and erratic early height growth and, in addition, so that site-index curves would be comparable to curves for other species including jack pine, black spruce, and plantation grown red pine and white spruce (Carmean, 1986, 1987, 1990).

Soil Description

Two one-metre-square soil pits were dug on each plot and a soil profile description was made for each pit according to standard Canadian methods (Bates *et al* . 1982; Canada Soil Survey Committee, 1978; Day,1983). All observations were recorded on a tally sheet designed by the O.M.N.R. (Appendix I).

Three mineral soil horizons (generally A,B, and C) were identified from each soil pit. Depth measurements to the nearest centimetre were recorded for the mineral horizons, and for the surface organic forest layers (L, F, and H, layers).

The soil descriptions recorded for each mineral horizon included texture, class, colour, mottle description, structure, consistence, boundary, coarse fragment content and root abundance. The soil descriptions and measurements of O.M.N.R.-FEC data were made using techniques described by Bates *et al.* (1982). Soil descriptions for plots established by Roddick were made using methods described in "Field Guide to the Forest Ecosystem Classification for Northwestern Ontario" (Sims *et al.,* 1990). The transformations of O.M.N.R.-FEC soil data information from the Bates' description to the Sims' description were made by Roddick and myself later so that all the data information were consistent for this study.

Soil texture in the field was determined from its feel, moist cast, taste, ability to ribbon, and the ability to reflect light called "shine". The determination of soil texture and the "soil texture triangle" (Sims *et al.,*

1990) were used to determine 18 different soil texture classes. Soil colour was evaluated in terms of hue, value, and chroma by comparing moist soil samples with colour chips from the Munsell colour book (Munsell Color Company, 1971); mottles were described in term of presence, size, abundance and colour to contrast with the soil matrix, and were classed by distinct or prominent mottles; soil structure was classified in terms of grade, class, and kind; distinctness and form were used to describe the horizon boundaries; soil consistency was estimated for soil in a moist state.

The percent coarse fragment content of each horizon was estimated by visually comparing area coverage charts to the pit face. Percent coarse fragments were divided into three fragment size classes: gravel (2.0 to 7.5 cm), cobbles (7.5 to 25 cm) and stones (greater than 25 cm). The abundance of roots in each horizon was expressed as the number of visible fine roots (1 to 2 mm in diameter) in a 10 cm square area of the pit face.

Additional descriptions were taken, including depth to bedrock, visible water table, water seepage, carbonates, mottles (faint mottles, distinct mottles, and prominent mottles), gley, bottom of maximum rooting, bottom of average rooting and bottom of visible rooting. The depth and presence of carbonates was determined through effervescense using 10% hydrocloric acid (HCl). Soil drainage class, pore pattern, moisture regime, FEC soil types and FEC vegetation types were determined using the key described in "Field Guide to the Forest Ecosystem Classification for Northwestern Ontario" (Sims *et al.*, 1990). Soil profile pictures were drawn for each soil pit to describe further the conditions of different soil horizons with detailed comments. The surface stones (%) and surface bedrock (%) in each plot were visually estimated where present.

Soil samples of approximately 1 kg weight were taken from each of the major horizons. Field samples included the soil as well as gravel sized coarse fragments.

Topographic Description

The latitude and longitude of each plot was determined from topographic maps. Topography of each plot was described in terms of total slope length (m), upslope length (m), aspect (azimuth degree), and slope steepness (%), site surface shape, and site position. Site surface shape was recorded as convex, straight and concave. Site position was recorded as crest (1), upslope (2), midslope (3), lower slope (4), toe slope (5), depression (6), and level (7). Each plot was assigned to three glacial landform categories: morainal, glaciofluvial and lacustrine.

LABORATORY ANALYSES

Soil samples were air dried and sieved to pass through a 2.0 mm sieve. Sticks, bark, roots and other foreign material were removed. The gravel remaining in the sieve was weighted and then discarded. The percent gravel content (> 2.0 mm) by weight was determined using the following formula:

$$\text{percent gravel} = \frac{\text{weight of gravel (g)}}{\text{weight of gravel plus fine earth (g)}} \times 100$$

The fine earth fraction was weighed and then mixed thoroughly in the sieve tray.

The soil analyses of the 42 O.M.N.R.-FEC plots were carried out at the Great Lakes Forestry Centre in Sault Ste. Marie, Ontario. The soil analyses of the Deschamps 56 plots (a total of 225 soil samples) were done by myself in the soils laboratory, School of Forestry, Lakehead University.

Four physical soil determinations were made including soil mechanical analysis, soil active acidity, soil reserve acidity, and soil organic matter content.

Soil Mechanical Analysis

The determination of sand, silt and clay was made by the Bouyoucos hydrometer method (McKeague, 1978). Two readings were recorded: a 40 second reading gave the amount of silt and clay , and a two hour reading gave the amount of clay. Percent of sand, silt and clay were calculated after adjustments for temperature.

Soil Acidity

Active acidity of soil (pH in distilled water) was determined for each horizon using calomel and glass electrodes in 25 ml distilled water. Reserve acidity of soil (pH in the KCL solution) was determined using the same method as used in active acidity analysis except readings were taken in 25 ml of 1N KCL solution instead of distilled water.

Soil Organic Matter Content

The organic matter content of soil was determined by loss on ignition. For each sample, 10 g soils were placed in an electric muffle furnace at 600° C for about 3 hours. Loss is calculated in percent based on the difference before and after heating.

All the soil laboratory analyses were accomplished using techniques described in the " Forest Soils Laboratory Manual" (Thrower and Schmidt, 1985).

Averaging Soil Laboratory Data

The number of recognized soil horizons usually differs for different soil pits and plots. For example, some soil pits have five or six different horizons, labelled " Ah, Bm, Bf, BC, C", or "Ah, Bm1, Bm2, Bf, BC, C". For these soils, there are five or six soil samples for each plot. In contrast, other soil pits have only one or two different horizons that might be labelled as "Bm", or "Bm, C". Most of these cases represent shallow soil situations. For computation purposes, data for all plots should be complete and consistent, therefore, the following methods were used to average the soil laboratory data:

1). Soils on most plots have four major horizons (most are A, B, BC, C horizons), thus the laboratory values for these four horizons on each plot were used as independent variables. For example, each plot had four values for organic matter content: organic matter in the A horizon, organic matter in the B horizon, organic matter in the BC horizon, and organic matter in the C horizon. These values for the four horizons were used in statistical analysis.

2).Some plots had more than four soil horizons thus there were more than four values from the laboratory analysis. Accordingly, values for similar horizons that had different suffixes were combined. For example, if the soil samples were labelled "A, Bm1, Bm2, BC, C", the values for the Bm1, and Bm2 were averaged as the value of the B horizon (Table 1).

3). Some plots had less than four soil horizons thus there were less than four values from the laboratory analysis. Accordingly, a double input of values was used. For example, if the sample only had two horizons " B, BC" , all the laboratory analysis values of B were entered into the spaces of A, and B; the values of BC were entered into the spaces of BC and C (Table 1).

Table 1. Examples of averaging soil laboratory data.

Situation	Soil analysis results		Computer data input	
	horizon	O.M.* data (%)	horizon	O.M.data (%)
more than four horizons	A	7.3	A	7.3
	Bm1	4.3	B	3.3
	Bm2	2.3	(average of Bm1 and Bm2)	
	BC	1.3	BC	1.3
	C	0.1	C	0.1
less than four horizons	B	3.5	A	3.5
			B	3.5 (double input)
	BC	1.0	BC	1.0
			C	1.0 (double input)

* O.M. means organic matter content.

STATISTICAL ANALYSES

The entire data set was analyzed by multivariate analysis. The statistical techniques which were used in this study are: principal component analysis (PCA), multiple regression analysis and cluster analysis (CA). They were used in the sequence illustrated in Figure 2:

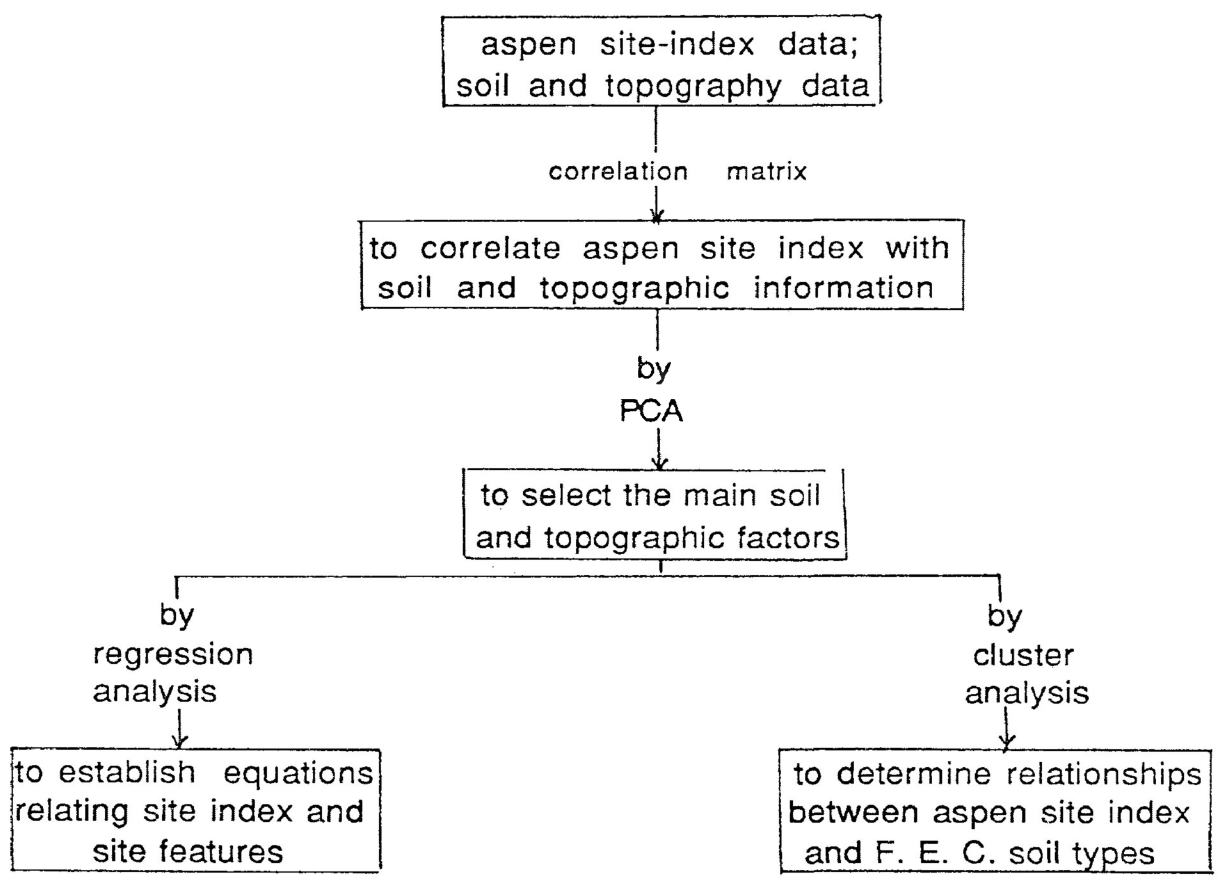


Figure 2. Statistical analysis procedures.

The simple correlation, regression, and cluster analyses used the SPSSX statistics package (Nie, 1983) on the Digital VAX 11/780 computer. The statistical computing system Minitab (Ryan *et al.*,1982) was used to carry out PCA on this computer. Graphics packages for the Macintosh Computer were used in the presentation of results.

Simple Correlation Analysis

Correlation analysis was used to identify variables that have a relatively high simple correlation with site index.

<u>The Variables, Scatterplots and Summary</u>

The dependent variable used in this study was site index (SI) of trembling aspen. Site index ($BHSI_{50}$) is defined as the height, in metres, of dominant and codominant trees at 50 years breast-height age.

Not all the values recorded on the soil field tally sheet were used in the statistical analysis. The criteria for selecting independent variables developed by Schmidt (1986) were used before computation. These criteria were as follows:

(1) the variable is available for each plot;
(2) the variable is not greatly affected by site disturbances;
(3) the variable could " reasonably" be expected to be related to site index;
(4) the variable either can be measured in the field or can be obtained through simple laboratory analyses.

Based on these four criteria, a total of 59 independent variables (soil and topographic values) were selected.

The dependent variable (SI) and the 59 independent variables used in the initial stages of analysis are listed in Table 2.

Table 2. List of variables.

A. Dependent Variable

SI = Site index ($BHSI_{50}$) is based on breast-height age measured as height in metres at 50 years from breast-height age.

B. Independent Variables

1. <u>Topography :</u>

Slo = Percent slope

Pos = Position on the slope. Coded as (1=crest; 2=upper; 3=middle; 4=lower; 5=toe; 6=depression; 7=level).

Asp = Aspect. Predominant aspect of the plot measured in azimuth degrees.

Slpl = Slope length. Measurement of the total length of the slope (m).

Sur = Surface shape. Coded as : (1=convex; 2=straight; and 3=concave).

2. <u>Soil texture :</u>

Sa(A) = Sand in the A horizon (0.05-2 mm) (%)

Sa(B) = Sand in the B horizon (%)

Sa(BC) = Sand in the BC horizon (%)

Sa(C) = Sand in the C horizon (%)

Sil(A) = Silt in the A horizon (0.002-0.05 mm) (%)

Sil(B) = Silt in the B horizon (%)

Sil(BC) = Silt in the BC horizon (%)

Sil(C) = Silt in the C horizon (%)

Cl(A) = Clay in the A horizon (< 0.002 mm) (%)

Cl(B) = Clay in the B horizon (%)

Cl(BC) = Clay in the BC horizon (%)

Cl(C) = Clay in the C horizon (%)

Sil+Cl(A) = Silt plus clay in the A horizon (%)

Sil+Cl(B) = Silt plus clay in the B horizon (%)

Sil+Cl(BC) = Silt plus clay in the BC horizon (%)

Sil+Cl(C) = Silt plus clay in the C horizon (%)

Table 2. List of variables (continued).

3. Coarse Fragment Content :

Coa(A) = Coarse fragments in the A horizon (%)

Coa(B) = Coarse fragments in the B horizon (%)

Coa(C) = Coarse fragments in the C horizon (%)

4. Soil depth

Dep = Depth to root restricting layer (cm) (mottles, gley, water table, bedrock, carbonates and /or basal till)

Thi(A) = Thickness of A horizon (cm)

Thi(Bf) = Thickness of Bf horizon (cm)

Thi(Bm)= Thickness of Bm horizon (cm)

Thi(Bf+Bm) = Thickness of Bf plus Bm horizon (cm)

Thi(BC)= Thickness of BC horizon (cm)

Thi(C) = Thickness of C horizon (cm)

Thi(Cg)= Thickness of Cg horizon (cm)

Thi(CG)= Thickness of CG horizon (cm)

T(A+Bf+Bm) = Thickness of A, plus Bf, plus Bm horizon (cm)

T(A+Bf+Bm+BC)= Thickness of A, plus Bf, plus Bm, plus BC horizon (cm)

Bed = Depth to bedrock (cm)

Carb = Depth to carbonates (cm)

Maxr = Depth of maximum rooting (cm)

Effer = Depth of effective rooting (cm)

Visr = Depth of visible rooting (cm)

Tab = Depth to water table (cm)

Seep = Depth to seepage (cm)

Mott = Depth to mottles (cm) (prominent mottles or distinct mottles)

Gley = Depth to gley (cm)

5. Soil moisture :

MR = Moisture regime. Coded as:(0=dry; 1=mod.fresh; 2=fresh;3=very fresh; 4=moderately moist; 5=moist; 6=very moist; 7=mod.wet; 8=wet; 9=very wet).

Table 2. List of variables (continued).

DC = Drainage class. Coded as: (1=very rapidly; 2=repidly;3=well; 4=moderately well; 5=imperfectly; and 6=poorly; 7=very poor).

6. Soil reaction (determined in the laboratory) :

pHw(A) = pH of the A horizon(in distilled water solution)
pHw(B) = pH of the B horizon (in distilled water solution)
pHw(BC)= pH of the BC horizon (in distilled water solution)
pHw(C) = pH of the C horizon (in distilled water solution)

pHK(A) = pH of the A horizon (in KCL solution)
pHK(B) = pH of the B horizon (in KCL solution)
pHK(BC) = pH of the BC horizon (in KCL solution)
pHK(C)= pH of the C horizon (in KCL solution)

7. Organic Matter Content. Expressed as a percent by weight of the soil (determined by labotory analysis) :

OM(A)= Organic matter in A horizon (%)
OM(B)= Organic matter in B horizon (%)
OM(BC)= Organic matter in BC horizon (%)
OM(C)= Organic matter in C horizon (%)

8. Litter Layer

LFH= Thickness of L.F. H layers (cm)

All the site index and soil and topography data were entered into the computer. All data files were compared to the original data sheets to verify that no entry errors occurred in the typing of these data sets.

Preliminary analyses were carried out between each independent variable and the dependent variable. Summary statistics including the mean, standard deviation, minimum, and maximum values for the dependent variable and for the independent variables were computed. Scatterplots relating site index to each independent variable were subsequently examined using SPSSX. The Pearson product-moment correlation (r) for SI with each independent variable was computed.

Study Plot Stratification

The simple correlation coefficients between site index and each independent variable were computed based on:

1) All 98 plots.
2) Each of the three broad landform categories: lacustrine, morainal and glaciofluvial.

All the plot data were carefully examined with the help of Dr. Carmean to confirm that they are in the correct catagories of the three different landforms. Three plots were discarded due to vague or atypical landform identifications. Data analyses were then carried out for each of these three landform types using 40 glaciofluvial plots, 35 morainal plots, and 20 lacustrine plots.

Definitions of each of these landforms were taken from Schmidt (Schmidt,1986; Schmidt and Carmean, 1988) and are defined as follows:

1. Lacustrine soils
   (a) the parent material is of glaciofluvial or glaciolacustrine origin; and
   (b) the fine earth fraction contains less than 50% sand.
2. Morainal soils
   (a) parent material is of glacial moraine origin; and
   (b) contains at least 10% coarse fragments.
3. Glaciofluvial soils
   (a) parent material is of glaciofluvial or of fluvial origin; and
   (b) fine earth fraction contains more than 50% sand.

Schmidt (1986) used shallow to bedrock morainal soils as an additional landform. In this study only a small number of plots occurred on shallow to bedrock morainal soils, thus these plots were included with the morainal soils.

The total number of plots used for each of the three glacial landforms, and the range of site index at 50 years breast-height age ($BHSI_{50}$), is listed in Table 3.

A large number of soil and topographic values were available for computation (Table 2). Variables eliminated from further analysis were those having low simple correlations with site index (probability of F greater than 0.05). Variables retained for further principal component analysis were those having a relatively high simple correlation with site index, i.e., variables that had a significance smaller than 0.05.

Table 3. Total number of plots by landforms and range of site index ($BHSI_{50}$).

Landform	Number of plots	Range of site index($BHSI_{50}$)(m)	Mean site index (m)	Standard deviation(m)
Glaciofluvial	40	15.5-25.1	20.0	2.3
Morainal	35	13.7-23.6	18.8	2.2
Lacustrine	20	17.0-25.1	20.6	2.5

Principal Component Analysis

A total of 22 soil and topographic variables had relatively high simple correlations with site index when all 98 plots were combined for analysis.

Most of those variables were highly correlated with each other. Thus, they are effectively expressing similar relations with site index. The backwards elimination method was used by Schmidt (1986) as a means of reducing the number of variables included in regression analysis. The method I used was principal component analysis to identify variables for use in regression analysis and cluster analysis.

"Principal component analysis consists of finding an orthogonal transformation of the original variables to a new set of uncorrelated variables, called principal components" (Chatfield and Collins, 1980). The first few components account for most of the variation in the original data. However, in application it is difficult to interpret these principal components in terms of the original variables. The PCA in this study was made in order to relate principal components to the original variables, i.e., to interpret PCA results in a meaningful way. The following steps were involved:

a).compute the eigenvalue and eigenvector of each principal component;

b).eliminate the original variable that had the largest absolute coefficient in the eigenvector of the last principal component;

c).compute the eigenvalue and eigenvector of each principal component again without this variable;

d).repeat this calculation several times until the eigenvalue of the last principal component explains a significant amount of variation and the number of original variables is small.

Those remaining original variables are the least correlated with each other and thus can be used as candidate variables for regression and cluster analysis (Luo and Xing,1987). Analyses showed that there were less than ten variables that had a relatively high simple correlation with site index within the three different glacial landforms. Consequently, the PCA described above was not applied to these landform categories.

Regression Analysis

The various soil and topographic features derived from simple correlation and from PCA were screened in order to select a set of variables that best predicted site index. The backwards elimination method of model selection was used. The variable with the largest probability of F value is removed, provided that this value is larger than the removal criterion. The default F value of 0.01 was specified.

Initial analysis indicated poor relationship when all 98 plots were combined into a single data set; further analysis was then restricted to using separate data sets for each of the three glacial landforms. Regression equations were then developed for the three landform groups. Each of these three landform equations related site index to a subset of soil and topographic variables.

Scatterplots of site index with each independent variable also were examined in order to verify the type of relationship existing between site index and each of the independent variables. Transformations of the various independent variables in the final regression equations included logarithmic, reciprocal and quadratic transpormations. The interaction between each of the independent variables (their products) also was explored to determine whether significant interactions existed.

Scatterplots of site index with each transformed variable and interaction variable also were examined. The equation with the highest coefficient of multiple determination (R^2), for a given standard error of the estimate, was considered to be the most precise equation. In addition, correlation between each of the independent variables was examined from a correlation matrix.

The residuals for each equation were then examined to determine if the assumptions of regression had been violated. These assumptions were:

1. The errors belonged to the population, i.e. no values outside the population. Bonferoni's t-test was used for detecting outliers (Weisberg, 1980);
2. The error terms were random. Scatterplots of the residuals vs. predicted values were studied to determine if nonlinearity or heteroscedasticity existed (Chatterjee and Price, 1977).

Due to the small size of the samples, only equations that included four or fewer independent variables were considered.

The estimated site index based on equations was compared to the actual site index observed from stem analysis on each plot. Residuals were computed by subtracting predicted site index from measured site index. These residuals were examined to determine whether possible biases existed in each of the final regression equations.

Cluster Analysis

Cluster analysis was used to determine relationships between aspen site index and F.E.C. soil types (Sims, *et al.*,1990). In this study, the measured distance between two plots is the sum of the squared differences between the values of the clustering variables. This measured distance is called the squared Euclidean distance. The computed equation is :

$$\text{distance}\ (X_1, X_2) = \sum_i (X_1 - X_2)^2$$

The complete linkage, or furthest neighbour method, was used as cluster linkage.

RESULTS

PRELIMINARY VARIABLE SCREENING

A total of 59 independent variables were defined (Table 2). However, soil profile descriptions for many of the older FEC plots lacked specific information for the following 10 variables:

-position on slope;
-aspect;
-slope length;
-surface shape;
-depth to bedrock;
-depth of maximum rooting;
-depth of effective rooting;
-depth of visible rooting;
-depth to water table;
-depth to seepage.

As a consequence, these 10 variables were eliminated from the analyses because a full statistical analysis requires that all plots have values for variables to be tested. Also laboratory analysis of soil pH in KCL solution was only made for the 56 Deschamps' plots; the 42 MNR-FEC plots did not have a laboratory analysis for soil pH in KCL solution. Thus soil pH in KCL solution could not be included in the statistical analysis. Accordingly, only a total of 45 independent variables were used for statistical analyses.

CORRELATION COEFFICIENTS

The simple correlation coefficients between site index and each of the 45 independent variable are given in Table 4. These correlation coefficients are listed for all 98 plots and are also separately listed for each of the three landform soil groups.

Table 4. Correlation coefficients between each independent variable and site index. (Coefficients are listed when all plots are combined as well as when plots are grouped into three different landforms).

Variable	Total plots	Glaciofluvial	Morainal	Lacustrine
Q1. Slo	-0.1607	-0.1887	-0.2062	0.0071
Q2. Sa(A)	-0.3301**	0.1015	-0.3481*	-0.2025
Q3. Sa(B)	-0.2508*	0.0934	-0.0722	-0.2210
Q4. Sa(BC)	-0.2867**	-0.0594	-0.1790	-0.4288
Q5. Sa(C)	-0.2322*	-0.1010	-0.2458	-0.3103
Q6. Sil(A)	0.3107**	-0.2200	0.4031*	0.1080
Q7. Sil(B)	0.2383*	-0.1440	0.1694	0.1065
Q8. Sil(BC)	0.1975	-0.0832	0.2310	-0.0722
Q9. Sil(C)	0.1234	-0.1469	0.2896	-0.1085
Q10. Cl(A)	0.1545	0.0830	-0.0325	0.1846
Q11. Cl(B)	0.1892	-0.0754	-0.0788	0.2635
Q12. Cl(BC)	0.3319**	0.3737	0.0293	0.4762*
Q13. Cl(C)	0.3145**	0.4989**	0.0618	0.7697**
Q14. Sil+Cl(A)	0.3129**	-0.1476	0.6468**	0.1953
Q15. Sil+Cl(B)	0.2568*	-0.0964	0.0886	0.2349
Q16. Sil+Cl(BC)	0.2917**	0.0750	0.2022	0.4192
Q17. Sil+Cl(C)	0.2357*	0.1205	0.2452	0.3047
Q18. Coa(A)	-0.4029**	-0.3113	-0.3901*	-0.2910
Q19. Coa (B)	-0.3719**	-0.1654	-0.3022	-0.1712
Q20. Coa (C)	-0.3874**	-0.2390	-0.7016**	-0.4056
Q21. Dep	0.3746**	0.6837**	0.4502**	0.4048
Q22. Thi(A)	-0.0037	-0.1793	0.2690	-0.4162
Q23. Thi(Bf)	0.1323	-0.1448	0.2488	-0.0981
Q24. Thi(Bm)	-0.0533	0.1998	-0.2375	-0.0705
Q25. Thi(Bf+Bm)	0.0437	-0.0078	-0.0629	0.0140
Q26. Thi(BC)	0.2722**	0.0428	0.4153*	-0.0504
Q27. Thi(C)	0.1826	0.2281	0.2012	0.1473
Q28. Thi(Cg)	0.2244*	0.2840	0.2134	0.3732
Q29. Thi(CG)	0.0892	0.2334	-0.0900	0.2464
Q30. Carb	-0.1145	-0.1177	-0.1544	0.1509
Q31. Mott	0.3812**	0.2453	0.4471*	0.6491**
Q32. Gley	0.1211	0.0767	-0.0900	0.3341
Q33. T(A+Bf+Bm)	0.0562	-0.0298	0.0314	-0.0994
Q34. T(A+Bf+Bm+BC)	0.1907	-0.0121	0.2955	-0.1923

Table 4. Correlation coefficients between each independent variable and site index. (Coefficients are listed when all plots are combined as well as when plots are grouped into three different landforms).

(continued)

Q35. MR	-0.1443	+0.2123	-0.1588	-0.2727
Q36. DC	-0.1204	+0.5026**	-0.0819	-0.3188
Q37. pHw(A)	0.1756	-0.0438	-0.1589	0.2334
Q38. pHw(B)	0.1544	-0.1235	0.0835	0.0798
Q39. pHw(BC)	0.1453	-0.1898	0.1004	-0.0034
Q40. pHw(C)	0.2122*	-0.0224	0.1001	0.0660
Q41. OM(A)	0.0695	0.1580	-0.0204	0.1618
Q42. OM(B)	-0.0318	-0.0524	0.1149	-0.1462
Q43. OM(BC)	-0.0191	0.1302	-0.0608	-0.0395
Q44. OM(C)	-0.2135*	0.1641	-0.2633	-0.1981
Q45. LFH	-0.2135*	-0.2191	0 .2137	-0.1242

* significance < 0.05 ** significance < 0.01

Analysis Combining All 98 Plots

When all 98 plots are combined for analysis, a total of 22 independent variables were significant at the 0.05 and 0.01 level (Table 4). These variables were usually various expressions at soil texture, depth to mottles and depth to a root restricting layer.

Soil Texture

The most important variable for predicting site index of trembling aspen was the percent coarse fragments found in the various soil horizons; coarse fragments in either the A, B or C horizons had a strong negative relationship with site index. For example, correlations between site index and coarse fragments content were: r=-0.4029 for the A horizon; r=-0.3719 for the B horizon; and r= -0.3874 for the C horizon. These levels of significance were less than 0.01 for all three horizons.

Texture of the various soil horizons, expressed as sand, silt and clay content, are also significantly related to site index. Sand content showed a negative relation with site index--- for the A horizon, r=-0.3301 (0.01 level); for the B horizon, r=-0.2508 (0.05 level); for the BC horizon, r=-0.2867 (0.01 level); for the C horizon, r=-0.2322 (0.05 level). Content of silt plus clay had a strong positive relation with site index in all the soil horizons---for the A horizon, r=0.3129 (0.01 level); for the B horizon, r=0.2568 (0.05 level); for the BC horizon, r=0.2917 (0.01 level); for the C horizon, r=0.2357 (0.05 level). Positive correlations for silt plus clay content indicates that better site indices were associated with greater amounts of silt plus clay in all horizons.

Soil Depth to Mottles

The depth to mottles (either distinct mottles or prominent mottles) was an important feature in relating aspen site index (r=0.3812, 0.01 level). This correlation indicates that better aspen site indices occur for soils having deeper depths to mottles.

Depth to Root Restricting Layer

Site index increased with increasing depth to root restricting layer. Correlations were positive for both depth to root restricting layer, and thickness of the BC horizon---for depth to root restricting layer,r=0.3746 (0.01 level), and for thickness of the BC horizon, r=0.2722 (0.01 level).

Many of the significant variables listed in Table 4 were highly correlated with each other. For example, r(Q2, Q3)=0.8323; r(Q2, Q6)=0.9314; r(Q2, Q14)=-0.9949; r(Q3, Q7)=-0.9327; r(Q3, Q15)=-0.9978, r(Q4,Q16)=-0.9951, r(Q4,Q17)=-0.9039, r(Q4,Q5)=0.9056, r(Q5,Q17)=-0.999, etc. Principal component analysis has been used in the next step to eliminate these highly correlated variables.

Analysis of Three Different Landform Soils

Glaciofluvial Soils

Correlation coefficients using only data from the 40 glaciofluvial plots showed that three variables were significant at the 0.01 level (Table 4). The highest correlation coefficient was the depth to root restricting layer (Q21)---r value between depth to a restricting layer and site index was 0.6837 (0.01). The second highest r value was for soil drainage---r=0.5026 (0.01). For the glaciofluvial soil group, most plots had sandy soils and thus were in drainage classes 1 (very rapidly), 2 (rapidly), 3 (well), or 4 (moderately well drained). Thus the positive correlation with soil drainage indicates that site index increases as drainage classes increase from class 1 to 4. Site index also was positively correlated with content of subsoil clay---r=0.4989. These positive correlations indicate that better site indices were associated with deep depths to root restricting layers, with well drained soils, and with soils having relatively large amounts of subsoil clay.

Morainal Soils

Correlation coefficients using only data from the 35 morainal plots showed that eight variables were significant at the 0.05 and 0.01 levels (Table 4). The most significant independent variable was the coarse fragment content of the C horizon---site index showed a strong negative correlation with this variable (r= -0.7016 at the 0.01 level). Also the coarse fragment content in both the A horizon and B horizon was negatively correlated with site index, but the correlations were not as strong as with the C horizon.

Strong positive correlations were also obtained between site index and the silt plus clay content of the A horizon (r=0.6468 --- 0.01 level); with silt content of the A horizon (r=0.4031---0.05 level); with soil depth to a root restricting layer (r=0.4502---0.01 level), with the depth to mottles (r=0.4471---0.01 level) and with the thickness of the BC horizon (r=0.4153--- 0.05 level). These results indicate that better sites for aspen were associated with increased silt plus clay content, with deep soils and with few coarse fragments in all soil horizons.

Lacustrine Soils

Correlation coefficients using only data from the 20 lacustrine plots showed that three variables were significant at the 0.05 and 0.01 level (Table 4). Site index of aspen in this landform increases with a heavy subsoil. The important variables were clay content in the C horizon (r=0.7697---0.01 level), and clay content in the BC horizon (r=0.4762---0.01 level), and depth to mottles (r=0.6491---0.01 level). Depth to root restricting layer (r=0.4048---0.05 level) was also included as this variable had a relatively high correlation even not statistically significant. These results indicate that better sites for aspen on lacustrine soils were associated with heavy-textured subsoils, and with soils that were deep to mottles or deep to other root restricting layers.

PRINCIPAL COMPONENT ANALYSIS

A total of 22 variables showed significant correlations with site index when all 98 plots were combined for analysis (Table 4). However, most of these variables were correlated with each other and thus express similar relations with site index. Accordingly, there was a need to reduce the number of variables to be used in the regression analysis and cluster analysis, and also a need to identify those variables that can best express effects of other associated independent variables. Principal component analysis is the method I used to accomplish this goal. The eigenvalues and eigenvectors of principal components were computed using Minitab for these 22 variables (Table 5).

Table 5. The eigenvalues of 22 principal components.

Principal component	Eigenvalue	Proportion	Cumulative
PC1	9.4602	0.430	0.430
PC2	3.1659	0.144	0.574
PC3	2.2130	0.101	0.675
PC4	1.7820	0.081	0.756
PC5	1.1240	0.051	0.807
PC6	0.8920	0.041	0.847
PC7	0.7498	0.034	0.881
PC8	0.5236	0.024	0.905
PC9	0.4985	0.023	0.928
PC10	0.4111	0.019	0.946
PC11	0.3543	0.016	0.962
PC12	0.2943	0.013	0.976
PC13	0.1748	0.008	0.984
PC14	0.1476	0.007	0.991
PC15	0.0763	0.003	0.994
PC16	0.0606	0.003	0.997
PC17	0.0392	0.002	0.999
PC18	0.0231	0.001	1.000
PC19	0.0050	0.000	1.000
PC20	0.0030	0.000	1.000
PC21	0.0012	0.000	1.000
PC22	0.0004	0.000	1.000

Table 5 shows that the first principal component accounted for 43.0 % of the variation in the original data. The next nine principal components (PC 2 to PC 10) accounted for an additional 51.6%, and the next seven principal components (PC 11 to PC 17) accounted for only 5.4 % of the variation in the original data while PC18 to PC22 contributed nothing in explaining the variation in the original data. These results mean that many of the original variables are not necessary for the subsequent regression analyses because their relations to site index can be described by other independent variables.

The eigenvector of the last, the 22th, principal component showed that

Q17 (silt plus clay of the C horizon) had the largest coefficient (0.59) among all 22 variables. Consequently, for the 21 remaining variables without Q17, the eigenvalues and eigenvectors of the principal components were recomputed. These results are given in Table 6.

Table 6. The eigenvalues of 21 principal components.

Principal component	Eigenvalue	Proportion	Cumulative
PC1	8.7687	0.418	0.418
PC2	3.1168	0.148	0.566
PC3	2.0857	0.099	0.665
PC4	1.7585	0.084	0.749
PC5	1.1184	0.053	0.802
PC6	0.8917	0.042	0.845
PC7	0.7474	0.036	0.880
PC8	0.5233	0.025	0.905
PC9	0.4960	0.024	0.929
PC10	0.3735	0.018	0.947
PC11	0.3393	0.016	0.963
PC12	0.2930	0.014	0.977
PC13	0.1728	0.008	0.985
PC14	0.1113	0.005	0.990
PC15	0.0738	0.004	0.994
PC16	0.0603	0.003	0.997
PC17	0.0374	0.002	0.998
PC18	0.0231	0.001	1.000
PC19	0.0049	0.000	1.000
PC20	0.0030	0.000	1.000
PC21	0.0010	0.000	1.000

These calculation were repeated 12 times and results indicated that the variables Q2, Q3, Q4, Q5, Q13, Q14, Q15, Q16, Q17, Q18, Q19, and Q28 could be eliminated because their relationships to site index could be expressed by other variables. The eigenvalues and eigenvectors of the remaining 10 principal components are presented in Table 7.

When Tables 5 and Table 7 are compared, we can see that the proportion of the total variation explained by the first principal component, as indicated by its eigenvalue, has been reduced from 43 % to 30 %. The last principal component accounted for only 2 % of the variation. Most of the variables have a major contribution to make in increasing the proportion of the total variation explained by each eigenvalue. Thus each of these ten original variables cannot be replaced by other variables in order to account for variation in site index. These 10 original variables are: silt in the A horizon (Q6), silt in the B horizon (Q7), clay in the BC horizon (Q12), coarse fragments in the C horizon (Q20), depth to root restricting layer (Q21), thickness of the BC horizon (Q26), depth to mottles (Q31), pH of the C horizon (Q40), organic matter of the C horizon (Q44), and thickness of the LFH layers (Q45). These ten variables were selected as candidate variables for regression and cluster analysis. These variables have little correlation with each other, and can be truly considered as independent variables.

Table 7. The eigenvalues of the remaining ten principal components.

Principal component	Eigenvalue	Proportion	Cumulative
PC1	3.0278	0.303	0.303
PC2	1.4522	0.145	0.448
PC3	1.2606	0.126	0.574
PC4	1.0619	0.106	0.680
PC5	0.8974	0.090	0.770
PC6	0.7517	0.075	0.845
PC7	0.5267	0.053	0.898
PC8	0.4484	0.045	0.943
PC9	0.3773	0.038	0.980
PC10	0.1960	0.020	1.000

REGRESSION ANALYSIS

Preliminary regression equations were computed by combining all 98 plots, for each of the three landforms (Table 3). For all 98 combined plots, the 10 variables were selected using principal component analysis and were those variables that had the highest simple correlations with site index. For the three different landform equations the variables having the highest significant simple correlations with site index were selected. These variables for the landform equations were selected from the correlation matrix and not by PCA as was done for the "all combined plots" regression. Ten candidate variables were used for the glaciofluvial landform, 11 candidate variables for the morainal landform, and nine candidate variables for the lacustrine landform. Variables used for each of the preliminary regression are listed in Table 8.

Table 8. Variables selected in the preliminary regressions together with their simple correlation coefficients with site index.

Variable	all plots	Glaciofluvial	Morainal	Lacustrine
Q1. Slo				
Q2. Sa(A)			-0.3481*	
Q3. Sa(B)				
Q4. Sa(BC)				-0.4288
Q5. Sa(C)				
Q6. Sil(A)	0.3107**		0.4031*	
Q7. Sil(B)	0.2383*			
Q8. Sil(BC)				
Q9. Sil(C)			0.2896	
Q10. Cl(A)				
Q11. Cl(B)				
Q12. Cl(BC)	0.3319**	0.3737		0.4762*
Q13. Cl(C)		0.4989**		0.7697**
Q14. Sil+Cl(A)			0.6468**	
Q15. Sil+Cl(B)				
Q16. Sil+Cl(BC)				0.4192
Q17. Sil+Cl(C)				
Q18. Coa(A)		-0.3113	-0.3901*	
Q19. Coa (B)			-0.3022	
Q20. Coa (C)	-0.3874**	-0.2390	-0.7016**	-0.4056
Q21. Dep	0.3746**	0.6837**	0.4502**	0.4048
Q22. Thi(A)				-0.4162

Table 8. Variables selected in the preliminary regressions together with their simple correlation coefficients with site index (continued).

Q23. Thi(Bf)				
Q24. Thi(Bm)				
Q25. Thi(Bf+Bm)				
Q26. Thi(BC)	0.2722**		0.4153*	
Q27. Thi(C)		0.2281		
Q28. Thi(Cg)		0.2840		0.3732
Q29. Thi(CG)		0.2334		
Q30. Carb				
Q31. Mott	0.3812**	0.2453	0.4471*	0.6491**
Q32. Gley				
Q33. T(A+Bf+Bm)				
Q34. T(A+Bf+Bm+BC)			0.2955	
Q35. MR				
Q36. DC		+0.5026**		
Q37. pHw(A)				
Q38. pHw(B)				
Q39. pHw(BC)				
Q40. pHw(C)	0.2122*			
Q41. OM(A)				
Q42. OM(B)				
Q43. OM(BC)				
Q44. OM(C)	-0.2135*			
Q45. LFH	-0.2135*			

* significance < 0.05 ** significance < 0.01

Table 9 lists the preliminary regression equations. Table 9 shows that the three soil landform equations have R^2 values from 0.63 to 0.65, and explain therefore about 63 to 65 % of the observed variation in site index. In contrast, the equation combining all plots only explained 48 % of the variation in site index. These results showed that greater precision in estimating site quality was obtained using separate landform soil groups. Accordingly, the three landform groups were analyzed further in an attempt to improve the prediction power of the equations.

Table 9. Preliminary regressions and associated statistics for all plots, and for the three glacial landforms.

Landform	Equation Number	Regression Equation	N	R^2	SEE (m)
Combined Landforms	U1	SI=17.345+0.0500Q12-0.3489Q20+ 0.0290Q26+0.0280Q31	98	0.48	1.71
Glacio-fluvial	G1	SI=17.696+0.146Q13-0.145Q18+ 0.062Q21-0.027Q28-0.479Q36	40	0.63	1.39
Morainal	M1	SI=14.532+0.031Q14-0.033Q20+ 0.044Q26+0.029Q31+0.026Q21	35	0.64	1.36
Lacustrine	L1	SI=17.812+0.284Q12-0.175Q13- 0.200Q20+0.052Q31	20	0.65	1.48

where:

SI= Site index ($BHSI_{50}$) is height (m) at dominant and codominant trees at 50 years breast-height age

N= Number of plots

R^2= Coefficient of multiple determination

SEE=Standard error of the estimate (m)

All the equations were tested to determine if they violated the assumptions of regression analysis mentioned on page 50; that is, to determine if errors belong to the same population; and to determine if errors are random and do not exhibit heteroscedasticity. Heteroscedasticity, or lack of it, was determined using scatterplots showing the relationship between predicted site index and each of the independent variables. To examine if error terms belonged to the same sample population (i.e. no outliers), Bonferroni's 't" test was used.

Glaciofluvial Landform

Data were collected from 40 plots. Five variables Q13 (clay in the C horizon), Q18 (coarse fragments in the A horizon), Q21 (depth to root restricting layer), Q28 (thickness of Cg), and Q36 (soil drainage class) were obtained in a preliminary regression analysis (Table 9). Various transformations (logarithmic, reciprocal and quadratic) expressing curvilinearity were then tested. Reciprocal variables were expressed as : 1/(the value of variable +1); logarithmic variables were expressed as : ln(the value of variable+1).

The scatterplot of site index versus Q21 (depth to root restricting layer) indicated a possible curvilinear relationship, thus various transformations expressing curvilinearity were tested to determine if significant improvements in the precision of equations could be made. Results showed that the reciprocal and the natural logarithm of Q21 did not increase the simple correlation coefficient with site index, however, the square of Q21 did improve the simple correlation coefficient. For the other four variables, the square of Q28, and the reciprocal of Q18 improved the simple correlation coefficient. Examination of scatterplots showed that none exhibited heteroscedasticity. Table 10 compares the simple correlation coefficients for these three transformed variables with the simple correlation coefficients using the original untransformed variables.

Regression equations using the five original variables and the three transformation variables were computed and the results are shown in Table 11. Results showed that even though the square of Q28 (thickness of Cg) and the inverse of Q18 (coarse fragments in the A horizon) improved the simple correlation coefficient (r) with site index, these transformed variables did not improve the precision (R^2) of the glaciofluvial landform regression equation. The square of Q21 (depth to root restricting layer) did improve the precision (R^2) of the glaciofluvial

Table 10. Comparisons for glaciofluvial soils between the simple correlation coefficients of the transformed variables and the simple correlation coefficients of the original untransformed variables.

	original	transformed	original	transformed	original	transformed
variable	Q18	1/(Q18+1)	Q21	$(Q21)^2$	Q28	$(Q28)^2$
r	-0.3113	-0.4692	0.6837	0.7146	0.2840	0.3078

r= simple correlation coefficient

equation, thus this transformed variable was retained in the regression (Table 11).

Table 11. Regression equation for glaciofluvial soils using the transformed variables.

No.	Equation	R^2	Adj.R^2	SEE(m)
G2	$SI=24.787+0.130(Q13)-0.148(Q18)+0.00200(Q21)^2$	0.64	0.60	1.39

where:

SI=Site index ($BHSI_{50}$) is height (m) of dominant and codominant trees at 50 years breast-height age

R^2= Coefficient of multiple determination

Adj.R^2= Adjusted R square

SEE= Standard error of the estimate

Q13= Clay in the C horizon (%)

Q18= Coarse fragment content of the A horizon (%)

Q21= Depth to root restricting layer (cm)

I next explored possible interaction transformations among the various significant variables. Such interactions could be used as an additional means of improving the precision of the glaciofluvial regression equation.

The following interaction terms were tested:

(1) Q13*(50-Q18), (2) Q13*Q21,
(3) Q13*Q28, (4) Q13*(10-Q36),
(5) (50-Q18)*Q21, (6) (50-Q18)*Q28,
(7) Q18*Q36, (8) Q28*Q21
(9) Q21*(10-Q36), (10) (10-Q36)*Q28.

Results showed three interaction terms increased simple correlation coefficient (r) values. These three terms are: Q21 and (10-Q36); (50-Q18) and Q21; Q28 and (10-Q36).

The final regression equation was computed using the five original variables, one significant transformation variable $(Q21)^2$ and three interaction variables. Results of these computations showed that one interaction term and one square term should be included in the final equation. Including these terms increased the R^2 value from 0.63 to 0.65; the final regression equation is given in Table 12. This equation did not violate any of the assumptions of regression.

The final G3 regression equation (Table 12) was used to compute trend graphs illustrating relations between site index and the two soil features used in the equation--- depth to root restricting layer, and drainage class (Figure 3). The final regression equation also was used to compute a site prediction table designed for use in the field estimation of site index for trembling aspen on glaciofluvial landform soils in Northwestern Ontario (Table 13). Note that this site-index prediction table should not be used for areas where soil drainage classes are greater than 4. The reason is that drainage classes that were observed in this analysis included only: (1) very rapidly drained, (2) rapidly drained, (3) well drained, (4) moderately well drained soils.

Table 12. The final regression equation for glaciofluvial landform soils.

No.	Regression equation	R^2	Adj.R^2	SEE
G3	$SI=16.429+0.00058(Q21)^2-0.003[Q21*(10-Q36)]$	0.65	0.64	1.38

where:

SI=Site index ($BHSI_{50}$) is height (m) of dominant and codominant trees at 50 years breast-height age

Q21= Depth to root restricting layer (cm)

Q36= Drainage class (1) very rapidly drained, (2) rapidly drained, (3) well drained, (4) moderately well drained .

Table 13. Site index ($BHSI_{50}$) prediction table for trembling aspen on glaciofluvial landform soils.

Depth to root restricting layer (cm)	Drainage class			
	1	2	3	4
	<---------Site index (m)----------------->			
30	16.1	16.2	16.3	16.4
60	16.9	17.1	17.3	17.4
90	18.7	18.9	19.2	19.5
120	21.5	21.9	22.3	22.6

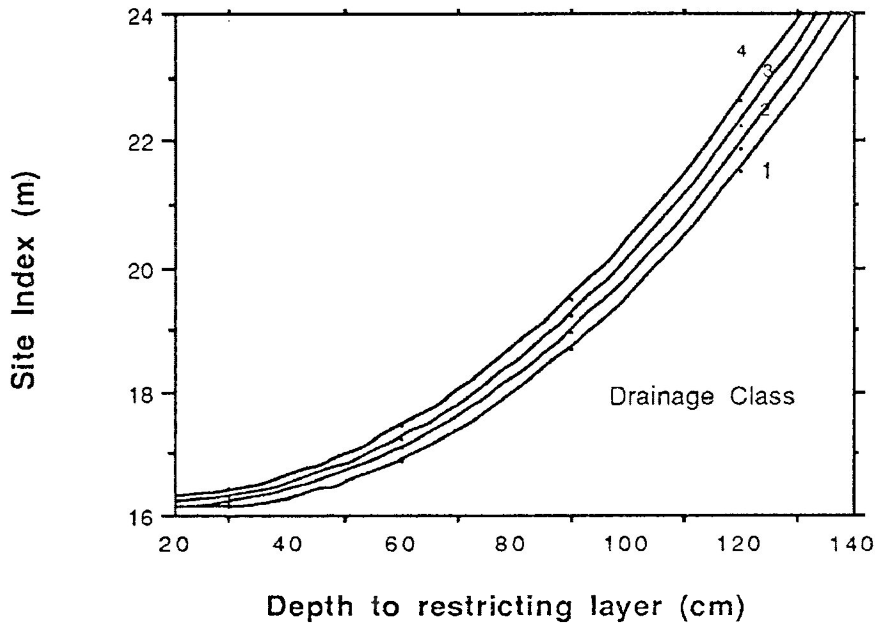


Figure 3. Trend graph illustrating relations between site index ($BHSI_{50}$) of trembling aspen, depth to root restricting layer and drainage class on glaciofluvial landform soils.

A final comparison was made to determine if possible biases existed in the final equation (G3). This comparison involved plotting site index data predicted by the final equation (G3) against site index observed on each of 40 plots (Figure 4). This comparison shows no obvious bias, thus equation G3 was accepted for use in estimating site index for trembling aspen in Northwestern Ontario.

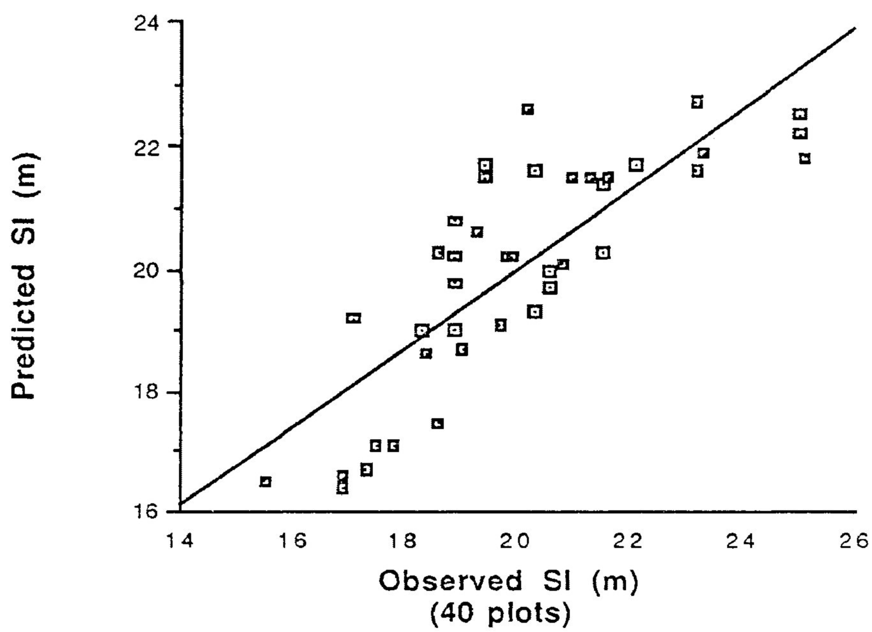


Figure 4. Comparison between predicted site index ($BHSI_{50}$) and observed site index using equation G3.

Morainal Landform

Data were collected from 35 morainal plots. Five variables Q14 (silt plus clay content in the A horizon), Q20 (coarse fragments in the C horizon), Q21 (depth to root restricting layer), Q26 (thickness of BC horizon), and Q31(depth to mottles) were analyzed in a preliminary regression equation (Table 9).

Various transformations expressing curvilinearity for these five variables were tested. The quadratic terms of variables Q21 and Q20 slightly increased the correlation coefficients with site index. Resulting regression equations containing these transformations together with their R^2, adjusted R^2, and standard errors of estimates are given in Table 14. None of the tranformations expressing curvilinear relations significantly increased R^2 values.

Table 14. Morainal regressions with the transformed variables.

No.	equations	R^2	adj.R^2	SEE
M3	$SI=17.582-0.00013(Q21)^2+0.052Q14-0.0455Q20$	0.64	0.61	1.35
M4	$SI=16.311-0.00052(Q20)^2+0.0169Q21+0.057Q14$	0.63	0.60	1.34

where:

SI=Site index ($BHSI_{50}$) is height (m) of dominant and codominant trees at 50 years breast-height age

Q21=Depth to root restricting layer (cm)

Q14=Silt plus clay content of A horizon (%)

Q20=coarse fragment content of C horizon (%)

Interaction terms were then tested in an attempt to improve further the precision (R^2) of the regression equation. The following interaction terms were tested:

(1) Q26*Q31.	(2) Q26*Q14.
(3) Q26* (100-Q20).	(4) Q26*Q21.
(5) Q31*Q14.	(6) Q31*(100-Q20).
(7) Q31*Q21.	(8) Q14*(100-Q20).
(9) Q21*Q14.	(10) Q21* (100-Q20).

Several regression equations were tested which, in various combinations, included the five original variables, the two significant transformations and ten interactions terms. The interaction term between Q14 and (100-Q20) slightly increased the R^2 value. The final regression equation is given in Table 15. Equation M5 meets the assumptions of regression.

Table 15. The final regression equation for the morainal landform.

No.	Equation	R^2	Adj.R^2	SEE
M5	$SI=14.97+0.00017(Q21)^2+0.00097[Q14^*(100-Q20)]$	0.66	0.63	1.32

where:

SI= Site index ($BHSI_{50}$) is height (m) of dominant and codominant trees at 50 years breast-height age

Q14= Silt plus clay in the A horizon (%)

Q20= Coarse fragments in the C horizon (%)

Q21= Depth to root restricting layer (cm)

The final regression equation (Table 15) was used to compute trend graphs showing the relationship between site index and the three independent variables Q14, Q20, Q21 (Figure 5, 6 and 7). The final equation (M5) also was used to construct a site index prediction table for use in the field estimation of site index of trembling aspen on morainal soils (Table 16).

Predicted site index using equation (M5) was plotted against observed site index (Figure 8). This graph indicates that the residuals or error terms are normally distributed and that the regression equation contains no biases when predicting site index on morainal landform soils. Thus the final regression equation (M5) is recommended for use in estimating site index of trembling aspen on morainal soils in Northwestern Ontario.

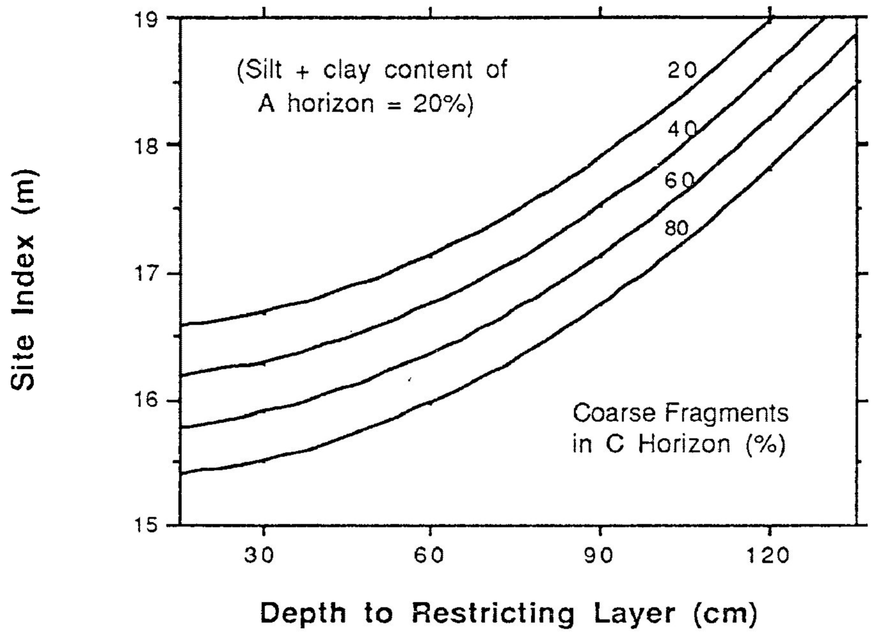


Figure 5. Trend graph illustrating relations between site index ($BHSI_{50}$) of trembling aspen, depth to root restricting layer, and coarse fragment content of C horizon on morainal landform soils having a silt+clay content in the A horizon of 20%.

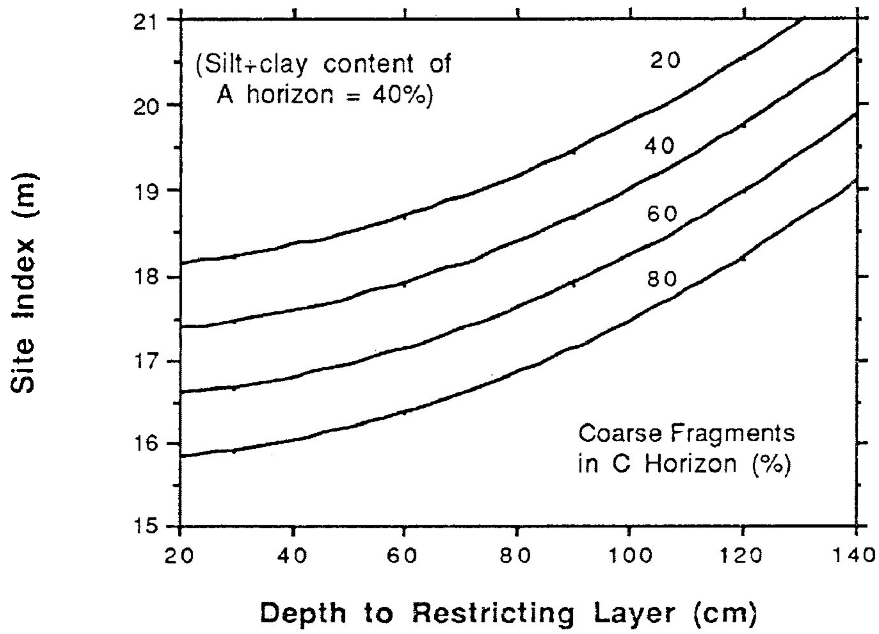


Figure 6. Trend graph illustrating relations between site index ($BHSI_{50}$) of trembling aspen, depth to root restricting layer, and coarse fragment content of C horizon on morainal landform soils having a silt+clay content in the A horizon of 40%.

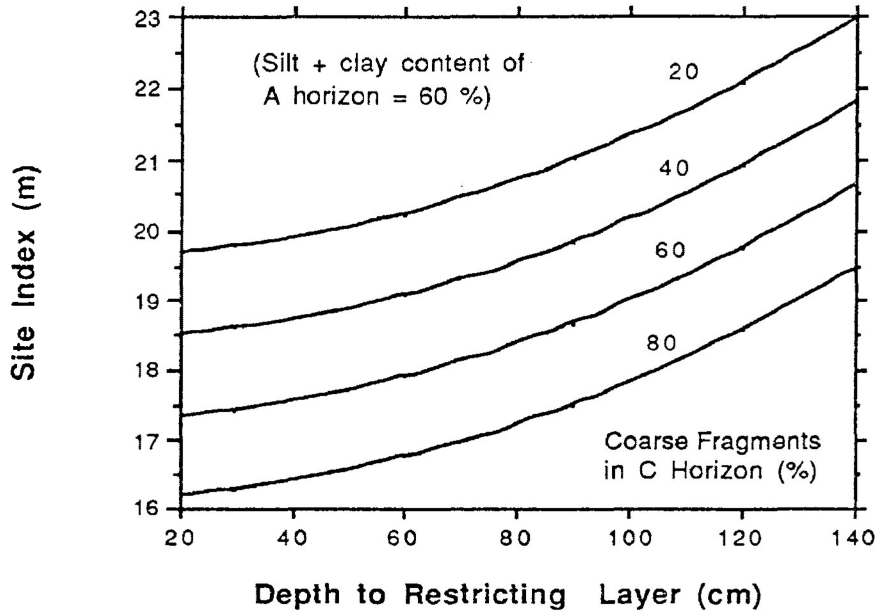


Figure 7. Trend graph illustrating relations between site index ($BHSI_{50}$) of trembling aspen, depth to root restricting layer, and coarse fragment content of C horizon on morainal landform soils having a silt+clay content in the A horizon of 60%.

Table 16. Site index ($BHSI_{50}$) prediction table for trembling aspen on morainal landform soils.

	Coarse fragments in C horizon (%) 20			40			60			80		
	silt plus clay content of the A horizon. (%) 20	40	60	20	40	60	20	40	60	20	40	60
Depth to root restricting layer (cm)	<----- Site index (m) ----->											
30	16.7	18.2	19.8	16.3	17.5	18.6	15.9	16.7	17.5	15.5	15.9	16.3
60	17.1	18.7	20.2	16.8	17.9	19.1	16.4	17.1	17.9	16.0	16.4	16.8
90	17.9	19.5	21.0	17.5	18.7	19.8	17.1	17.9	18.7	16.7	17.1	17.5
120	19.0	20.5	22.1	18.6	19.8	20.9	18.2	19.0	19.8	17.8	18.2	18.6

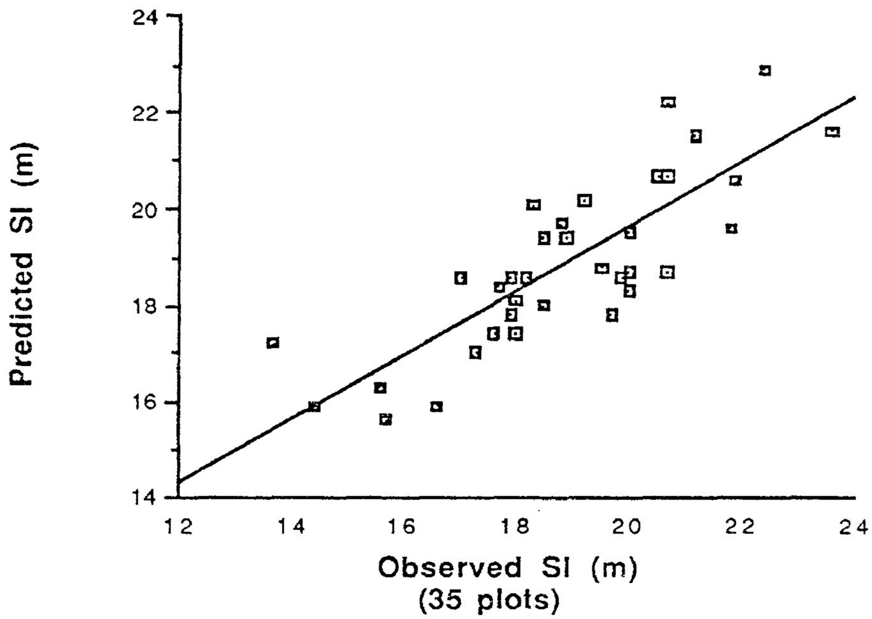


Figure 8. Comparison between predicted site index ($BHSI_{50}$) and observed site index using equation M5.

Lacustrine Landform

Data were collected from 20 plots. Four variables Q12 (clay in the BC horizon), Q13(clay in the C horizon), Q20 (coarse fragments in the C horizon), and Q31 (depth to mottles) were analyzed in a preliminary regression equation (Table 9).

The scatterplots of site index versus Q12, Q13 and Q31 indicated possible curvilinear relationships. These possible curvilinear relationships were tested using quadratic, reciprocal and logarithmic transformations. Results showed that the square of Q31, the square of Q20, and the natural logarithm of Q13 improved the simple correlation coefficient with site index (Table 17). However, when these transformed variables were added to the regression, result showed that only the logarithmic transformation of clay in the C horizon (Q13) improved the precision (R^2) of the lacustrine equation (L2). (Table 18).

Table 17. Comparisons for lacustrine soils between the simple correlation coefficients of the transformed variables and the simple correlation coefficients of the original untransformed variables.

	original	transformed	original	transformed	original	transformed
variable	Q13	ln(Q13+1)	Q31	$(Q31)^2$	Q20	$(Q20)^2$
r	0.7697	0.7985	0.6491	0.6511	-0.4100	-0.4600

r= simple correlation coefficient

Table 18. Regression equation with the transformed variables.

No.	Equation	R^2	Adj.R^2	SEE
L2	SI=19.359+0.276Q12-0.115Q13+ +0.042Q31-1.55Qln(Q13+1)	0.66	0.63	1.48
L3	SI=16.66+0.265Q12-0.176Q13 +0.04Q31-0.01$(Q20)^2$	0.65	0.62	1.74

where:

SI=Site index ($BHSI_{50}$) is height (m) of dominant and codominant trees at 50 years breast-height age

Q12= Clay content of BC horizon (%)

Q13= Clay content of C horizon (%)

Q20=Coarse fragment content of C horizon (%)

Q31= Depth to mottles (cm)

Interaction terms were then tested in an attempt to further improve precision (R^2) of the regression equation. The following interaction terms were tested:

(1). Q12*Q13. (2). Q12*(30-Q20).
(3). Q13*Q31. (4). Q12*Q31
(5). Q13*(30-Q20). (6). Q31*(30-Q20).

The final equation was derived from the four original variables, one significant transformation variable and the 10 interaction variables. The final regression equation (L4) is given in Table 19. Equation L4 meets the assumptions of regression.

Table 19. The final regression equation for lacustrine landform.

No.	Equation	R^2	Adj.R^2	SEE
L4	SI=21.2+0.0021(Q13*Q31)-1.508ln(Q13+1)	0.68	0.65	1.46

where:

SI=Site index ($BHSI_{50}$) is height (m) of dominant and codominant trees at 50 years breast-height age

Q13= Clay content of C horizon (%)

Q31= Depth to mottles (cm)

The final regression equation (L4) was used to construct a trend graph illustrating how site index of trembling aspen is related to depth to mottles (Q31) and clay content of the C horizon (Q13) (Figure 9). Comparisons between observed site index from stem analysis and predicted site index based on equation (L4) showed no apparant bias in the prediction equation (Figure 10). The final regression equation L4 was used to compute a site-index prediction table for use in predicting site index of trembling aspen on lacustrine landform soils (Table 20).

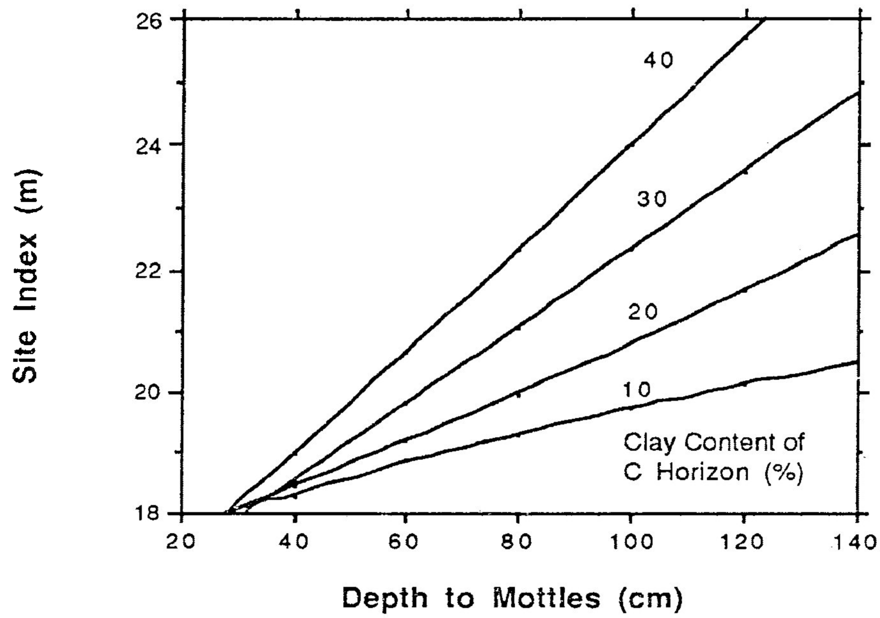


Figure 9. Trend graph illustrating relations between site index ($BHSI_{50}$) of trembling aspen, depth to mottles, and clay content of the C horizon on lacustrine landform soils.

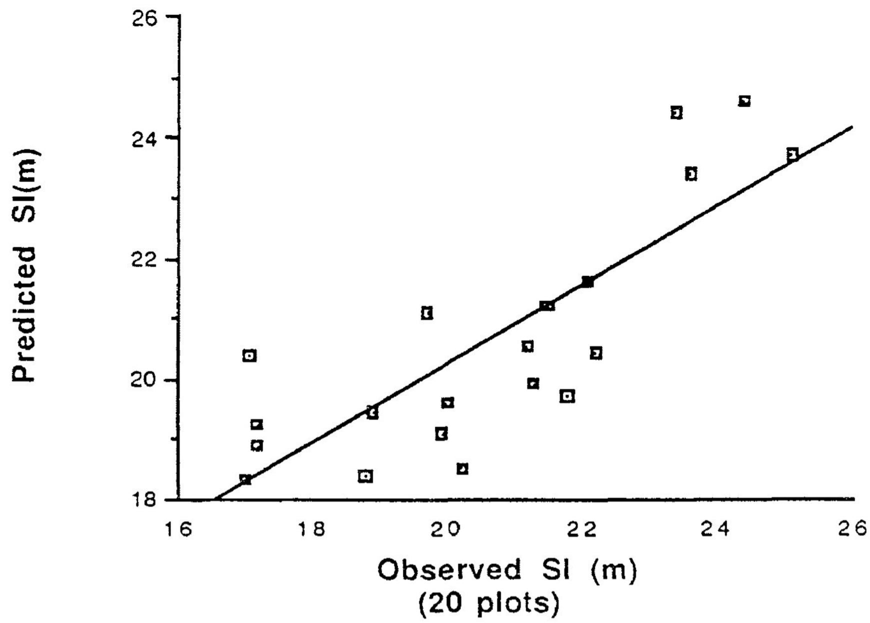


Figure 10. Comparison between predicted site index ($BHSI_{50}$) and observed site index using equation L4.

Table 20. Site index (BHSI 50) prediction table for trembling aspen on lacustrine landform soils.

Depth to mottles (cm)	Clay content of C horizon (%)			
	10	20	30	40
	<---------Site	index	(m)---------------	>
40	18.3	18.4	18.5	18.9
60	18.9	19.2	19.8	20.6
80	19.3	19.9	21.1	22.3
100	19.7	20.8	22.3	24.0
120	20.1	21.7	23.6	25.7

CLUSTER ANALYSIS

Cluster analysis was used to determine relationships between aspen site index and soil types described by the FEC (Forest Ecological Classification) system for Northwestern Ontario (Sims *et al.,* 1990). Twelve variables were used as cluster variables with ten variables based on results of principal component analysis (Table 7). These ten variables included silt in the A horizon (Q6), silt in the B horizon (Q7), clay in the BC horizon (Q12), coarse fragments in the C horizon (Q20), depth to root restricting layer (Q21), thickness of the BC horizon (Q26), depth to mottles (Q31), pH in the C horizon (Q40), organic matter in the C horizon (Q44), and thickness of the LFH layer (Q45). These ten variables were significantly related to aspen site index and were not closely correlated with each other.

The remaining two variables were soil moisture regime and soil drainage class. The reasons for using these two variables are: (1) they are important features in FEC soil type classification; and (2) the range of the observed soil moisture regimes and soil drainage classes are very wide. In all study plots, moisture regimes ranged from 0 to 6, a total of 7 classes; drainage classes ranged from 1 to 6, a total of 6 classes. Soil moisture regime and soil drainage classes were not used in regression analysis because it is difficult to analyze the relationship between independent variables that are measured on an ordinal scale and dependent variables, such as site index, that are continuous. Therefore, although these two variables did not show a close correlation with site index, they were still important factors and were, therefore, considered in the cluster analysis.

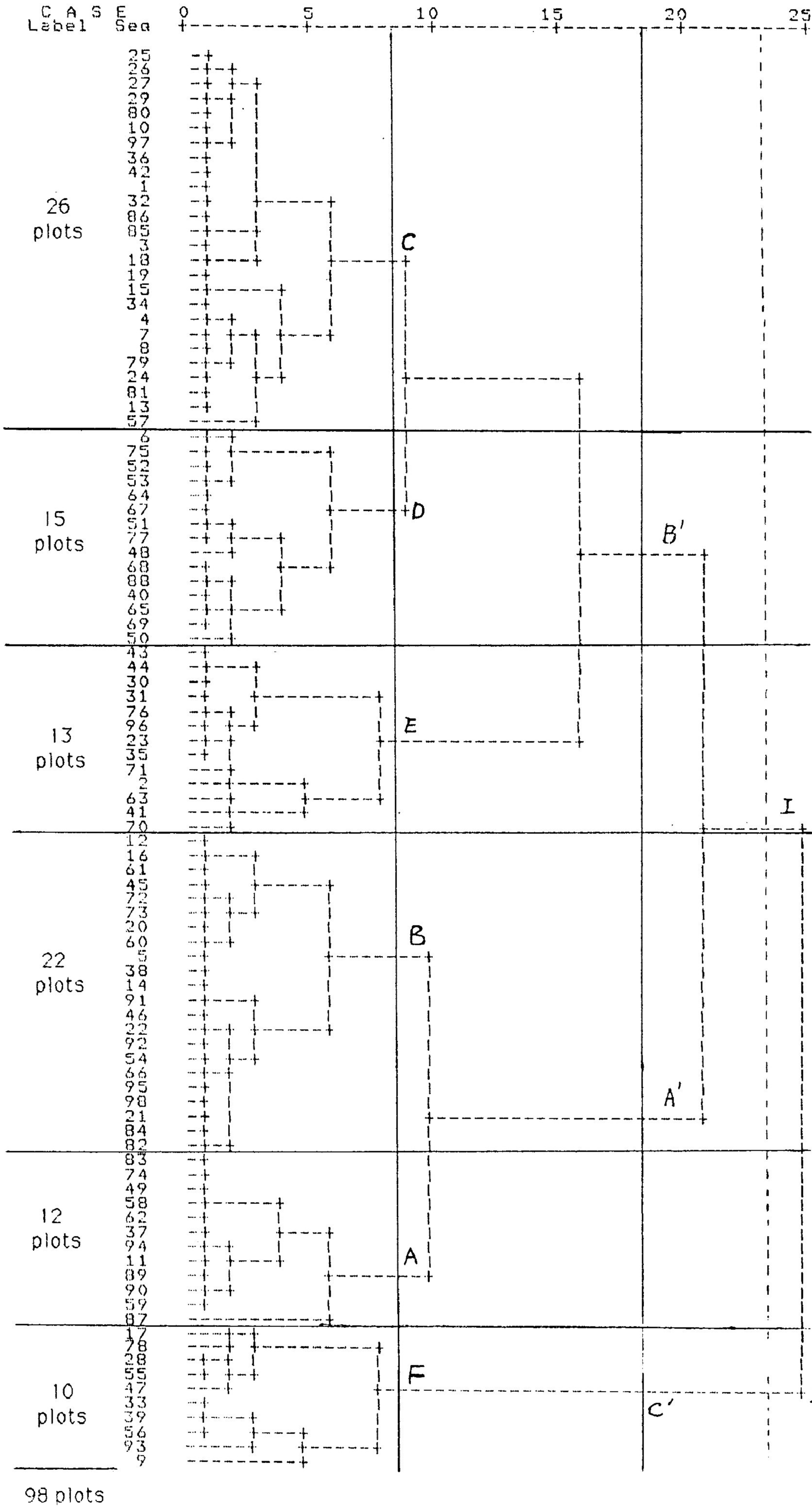
The 98 by 12 data matrix (98 plots and 12 variables) were entered into the computer. The cluster analysis results are shown in Figure 11 with the identification numbers of the 98 plots shown on the left of the figure. The plots were clustered based on their squared distances from each other, and clusters include individual plots that show similarities. At the relative distance 8 to 9, all 98 plots were clustered into 6 groups, referred to as A, B, C, D, E, and F. Table 21 lists the number of plots among these 6 groups. At the relative distance from 16 to 21, the 98 plots were clustered into 3 groups, called A', B' and C' (Figure 11). The A' group comes from the plots of groups A and B , a total of 34 plots; the B' group is made up of the plots of groups C, D, and E , a total of 54 plots; the C' group includes only the F group, a total of 10 plots. The cluster results of A', B', and C' showed that A and B are similar, C, D, and E are similar; and the F group is different from the other five groups. At the relative distance from 22 to 24.5, the 98 plots were clustered into two groups, called I and II (Figure 11). The A, B, C, D, E groups were clustered together, which is I, and the F group forms II. The biggest difference exists between the F group and the other five groups.

Table 21. The number of plots for each cluster group.

group	A	B	C	D	E	F	Total
plots	12	22	26	15	13	10	98

The site index of aspen and soil features among these 98 plots were analyzed based on the 6 groups. The total range of site index among the 98 plots was from 13.7 to 25.1 m (Table 3). This site index range was subdivided into 8 classes of site index: 13.0-14.9 m; 15.0-16.9 m; 17.0-17.9 m; 18.0-18.9 m; 19.0-19.9 m; 20.0-20.9 m; 21.0-22.9 m; 23.0-25.1 m. The first four classes (13.0-18.9 m) were defined as the lower site index in this study, with the other four classes (19.0-25.1 m) defined as the higher site index. Figure 12 shows the percentage of the lower site index distribution among these six groups. From A to F, the percentage of the lowest site index increases. Figure 13 shows the percentage of the higher site index distribution among these six groups. From A to F, the

Figure 11. Cluster analysis results.



Note: The numbers on the left side of the figure are the identification number of each plot. The relative distances are shown on the top of the figure.

percentage of higher site index decreases. The A group represents the best site index for trembling aspen, while the F group represents the worst. The remaining groups are intermediate. The detailed analyses are presented in Tables 22 to 34.

The Analysis of the A Group

The site index information and soil information in the A group are given in Tables 22 and 23, respectively.

Table 22. Site index ($BHSI_{50}$) information for the A group.

Total plots: 12
average SI: 21.75 m

Range of site index	13.0-14.9 m	15.0-16.9 m	17.0-17.9 m	18.0-18.9 m	19.0-19.9 m	20.0-20.9 m	21.0-22.9 m	23.0-25.1 m
No. of plots	none	none	1	none	2	1	3	5
Aver. site index	none	none	17.0	none	19.6	20.0	21.7	23.9
% in the group			8.3%		16.7%	8.3%	25%	41.7%

Table 22 shows that only 1 plot with a site index value of 17.0 m occurs in the lower site index range,--- this plot represents 8.3% of all the plots in the A group. The remaining 11 plots are in the higher site index ranges--- 6 plots are in the 19.0 m to 22.9 m range; and 5 plots in the 23.0-25.1 m range. Thus the A group has 91.7% of all plots in the higher site index ranges (19.0-25.1 m); the very highest site index range (23.0 m-25.1 m) account for 41.7% of all plots in the A group.

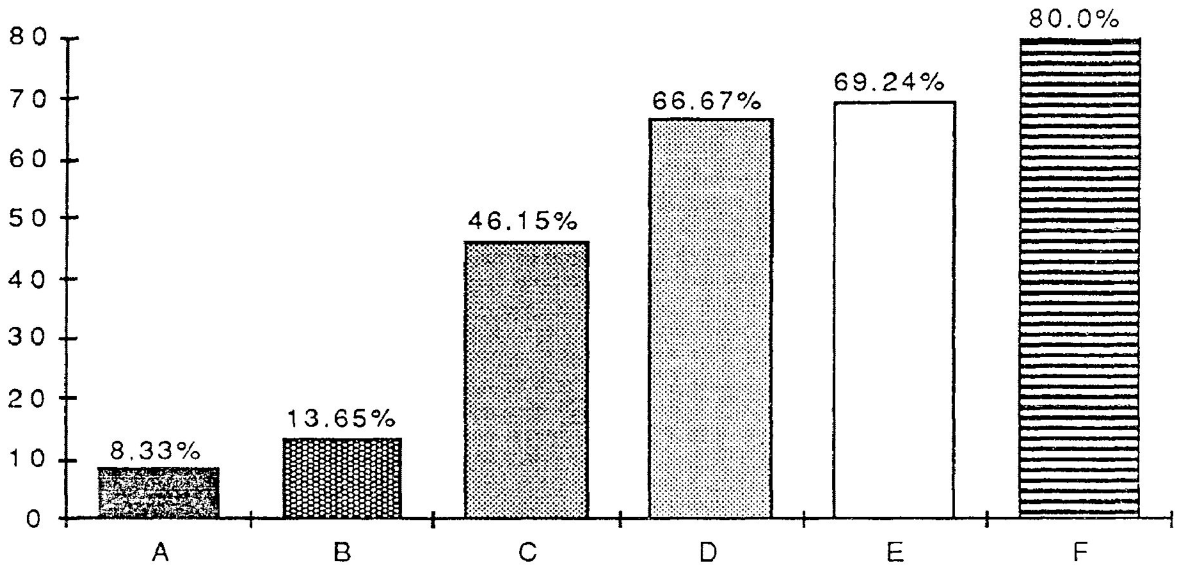


Figure 12. Lower site index (13.0-18.9 m) percentage among six groups.

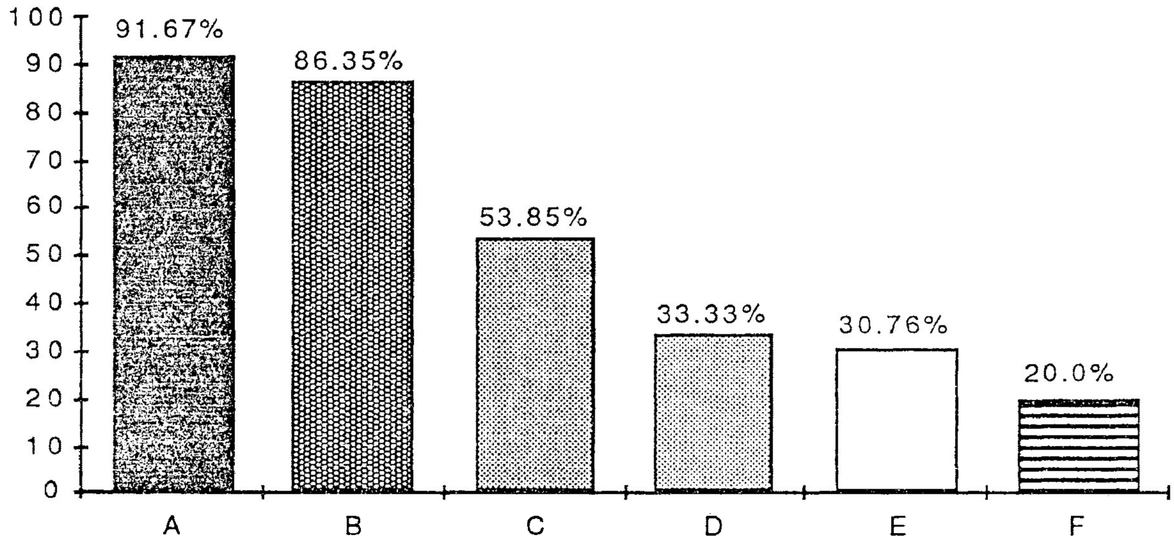


Figure 13. Higher site index (19.0-25.1 m) percentage among six groups.

Table 23. Soil information for the A group.

Items			Percentage
Soil types	main	S3, S4, S5. (fresh/loamy)	75%
	other	S2 (fresh/fine sandy) S6 (fresh/clayey)	25%
Depth to RRL*	main	deep soil, greater than 120cm	100%
	other	0	0%
Moisture regime	main	2 (fresh)	83.3%
	other	0 (dry), 1(mod.fresh)	16.7%
Drainage class	main	3 (well)	83.3%
	other	2 (rapidly), 4 (mod.well)	16.7%
Presence of mottles	main	no mottles	100%
	other	0	0%
Average coarse fragment (%)			7.1%
Average pH value			6.35

*RRL: root restricting layer

Table 23 lists the soil characterastics of the A group. Most soil types are of the S3, S4, S5 variety (75%). All the plots are in deep soils (depth to root restricting layer is greater than 120 cm), and no mottles appear in the entire soil profile. The main soil moisture regime is 2 (fresh), and drainage class is 3 (well drained).

The Analysis of the B Group

The site index and soil information in the B group are given in Tables 24 and 25, respectively.

Table 24. Site index ($BHSI_{50}$) information for the B group.

Total plots: 22
average SI: 20.63 m

Range of site index	13.0-14.9 m	15.0-16.9 m	17.0-17.9 m	18.0-18.9 m	19.0-19.9 m	20.0-20.9 m	21.0-22.9 m	23.0-25.1 m
No. of plots	none	1	1	1	3	6	8	2
Aver. site index	none	15.5	17.1	18.9	19.7	20.5	21.7	23.2
% in the group		4.6%	4.6%	4.6%	13.6%	27.3%	36.4%	9.1%

Table 25. Soil information for the B group.

Items			Percentage
Soil types	main	S1, S2, S3. (dry-fresh/coarse, fine sandy,loamy)	77.3%
	other	S4,S5,S6 (fresh/loamy-clayey) SS6 (shallow/coarse-loamy)	22.7%
Depth to RRL*	main	deep soil, greater than 120 cm	90.9%
	other	shallow soil (average: 82 cm)	9.1%
Moisture regime	main	1 (mod.fresh), 2 (fresh)	77.3%
	other	0 (dry), 3(very fresh)	22.7%
Drainage class	main	2 (rapidly) 3 (well)	77.3%
	other	4 (mod.well)	22.7%
Presence of mottles	main	no mottles	95.5%
	other	depth to mottles averages 91cm	4.5%
Average coarse fragments (%)			9.6%
Average pH value			5.89

*RRL: root restricting layer

Table 24 shows that there are three plots in the lower range of site index (15.0-18.9 m). These three plots represents 13.8 % of the B group. The remaining 19 plots are distributed in the higher site index ranges (19.0 - 25.1 m). The percentage (13.8%) of lower site index plots is higher than in the A group.

Soil conditions are somewhat more sandy and dry than those in the A group (Table 25): 77.3% of soil types are S1, S2, S3. Most plots still have deep soils, greater than 120 cm. Soil moisture classes are drier and the main moisture regimes are 1 (mod. fresh), and 2 (fresh). Soil water drains more rapidly than in the A group, and the main drainage classes are 2 (rapidly) and 3 (well drained).

The Analysis of the C Group

Average site index of the C group (Table 26) is somewhat lower than that of the A and B groups. Most plots (14) are in the site index range from 18.0-19.9 m, and account for 53.9% of the plots. However, there are four plots (15.4%) in the low site index range from 15.0 to 17.9 m. The percentage in the lower SI range (13.0-18.9 m) becomes greater (46.2%) than in the A and B groups.

Table 26. Site index ($BHSI_{50}$) information for the C group.

Total plots: 26
average SI: 19.6 m

Range of site index	13.0-14.9 m	15.0-16.9 m	17.0-17.9 m	18.0-18.9 m	19.0-19.9 m	20.0-20.9 m	21.0-22.9 m	23.0-25.1 m
No. of plots	none	2	2	8	6	3	3	2
Aver. site index	none	16.3	17.8	18.6	19.6	20.2	21.7	25.1
% in the group		7.7%	7.7%	30.8%	23.1%	11.5%	11.5%	7.7%

Soil conditions (Table 27) are drier, and sandier than for the B group. Most FEC soil types are S1 and S2; soil moisture regimes are 0 (dry) and 1 (mod. fresh); drainage classes are 1 (very rapidly drained) and 2 (rapidly drained). More coarse fragments (22.9% average) occur in the soil surface.

Table 27. Soil information for the C group.

		Items	Percentage
Soil types	main	S1, S2. (Dry-Fresh/sandy)	88.5%
	other	S3 (Fresh/coarse-loamy) SS5 (shallow/sandy)	11.5%
Depth to RRL*	main	deep soil, greater than 120cm	96.2%
	other	shallow soil. (average: 75cm)	3.9%
Moisture regime	main	0 (dry), 1(mod.fresh)	80.8%
	other	2 (fresh)	19.2%
Drainage class	main	1 (very rapidly), 2 (repidly)	76.9%
	other	3 (well), 4 (mod.well)	23.1%
Presence of mottles	main	no mottles	100%
	other	0	0 %
Average coarse fragments (%)			22.9%
Average pH value			5.69

*RRL: root restricting layer

The Analysis of the D and E Groups

Average site indices for the D and E groups are almost exactly the same (Tables 28 and 29). The percentage of the lower site index range (13.0-

18.9 m) is about 66-69%. The percentage of the higher site index range (19.0-25.1 m) is about 30-33%. Average site indices are similar but are lower than in the A, B, and C groups. Even though site indices are similar, the soil characteristics of the D and E groups are very different (Table 30 and 31).

Table 28. Site index ($BHSI_{50}$) information for the D group.

Total plots: 15
average SI: 18.7 m

Range of site index	13.0-14.9 m	15.0-16.9 m	17.0-17.9 m	18.0-18.9 m	19.0-19.9 m	20.0-20.9 m	21.0-22.9 m	23.0-25.1 m
No. of plots	none	1	6	3	1	2	2	none
Aver. site index	none	16.9	17.4	18.6	19.7	20.3	21.4	none
% in the group		6.7%	40%	20%	6.7%	13.3%	13.3%	

Table 29. Site index ($BHSI_{50}$) information for the E group.

Total plots: 12
average SI: 18.7 m

Range of site index	13.0-14.9 m	15.0-16.9 m	17.0-17.9 m	18.0-18.9 m	19.0-19.9 m	20.0-20.9 m	21.0-22.9 m	23.0-25.1 m
No. of plots	1	2	1	5	1	1	none	2
Aver. site index	14.4	16.1	17.3	18.4	19.2	20.0	none	24.4
% in the group	7.7%	15.3%	7.7%	38.5%	7.7%	7.7%		15.4%

Eighty percent of the soil types in the D group belong to the S7, and S8 soil types (Table 30). Therefore, moisture regime 4 (mod. moist) and 5 (moist) are the main moisture regimes, class 5 (imperfectly drained) is the main drainage class. Mottles appeared in all soils with an average depth to mottles of 54 cm. Too much soil water exists in the soil profile even though deep depths to root restricting layers occur. There are fewer coarse fragments, and the pH is high, but these conditions are not associated with best aspen growth.

Table 30. Soil information for the D group.

Items			Percentage
Soil types	main	S7 (moist/sandy), S8 (moist/coarse-loamy)	80%
	other	S9 (moist/silty), S3 (fresh/coarse-loamy)	20%
Depth to RRL*	main	deep soil, greater than 120 cm	93.3%
	other	shallow soil (average 52 cm)	6.7%
Moisture regime	main	4 (mod.moist), 5 (moist)	73.3%
	other	3 (very fresh), 2(fresh)	26.7%
Drainage class	main	5 (imperfectly)	93.3%
	other	4 (mod.well)	6.7%
Presence of mottles	main	depth to mottles is less than 70 cm, average depth is 53.9 cm	100%
	other	0	0%
Average coarse fragments (%)			13.4%
Average pH value			6.48

*RRL: root restricting layer

The soil conditions in the E group (Table 31) are different from conditions in the D group. Soils are usually dry and mottles cannot be found in almost 70% of the plots. However, 77 % of the plots are in shallow soils with depth to root restricting layer being only 10 - 11 cm in two plots; another two plots are in 60 cm deep soil; but many coarse fragments occur with an average content of about 66%.

Table 31. Soil information for the E group.

		Items	Percentage
Soil types	main	SS5, SS4, (shallow/sandy), S7 (moist/sandy)	76.9%
	other	S2, S3 (Fresh/coarse-loamy)	23.1%
Depth to RRL*	main	shallow soil (average 56.71cm)	53.9%
	other	deep soil, greater than 120 cm	46.2%
Moisture regime	main	0 (dry), 1 (mod.fresh) 4 (mod. Moist)	76.9%
	other	3 (very fresh), 2(fresh)	23.1%
Drainage class	main	1(very rapidly), 2 (rapidly), 5 (imperfectly)	100%
	other	0	0
Presence of mottles	main	no mottles	69.2%
	other	depth to mottles averages 54.7 cm	30.8%
Average coarse fragments (%)			65.9%
Average pH value			5.57

*RRL: root restricting layer

The Analysis of the F Group

The F group has the lowest average site index among the six soil groups. Only 20 % of the plots have site indices in the 20.0-22.9 m ranges, and no plots are found in the highest site index range (> 22.9 m). The remaining 80% of the plots are in the lower ranges (Table 32). The unfavourable soil conditions noted for groups D and E are even more pronounced for the F group (Table 33). Mottles appear in all plots, the average depth to mottles is only 16 cm, and 60% of the plots are in shallow soil. The main soil

Table 32. Site index ($BHSI_{50}$) information for the F group.

Total plots: 10
average SI: 17.8 m

Range of site index	13.0-14.9 m	15.0-16.9 m	17.0-17.9 m	18.0-18.9 m	19.0-19.9 m	20.0-20.9 m	21.0-22.9 m	23.0-25.1 m
No. of plots	1	1	4	2	none	1	1	none
Aver. site index	13.7	15.7	17.3	18.7	none	20.6	21.0	none
% in the group	10.0%	10.0%	40%	20%		10.0%	10.0%	

Table 33. Soil Information for the F group.

		Items	Percentage
Soil types	main	SS8 (shallow/mottle-gley), SS7 (shallow/silty)	60%
	other	S8,S9, S7 (moist/sandy-silt) S12F (wet/organic)	40%
Depth to RRL*	main	shallow soil. (average: 56.8 cm)	60%
	other	deep soil , greater than 120 cm	40%
Moisture regime	main	6 (very moist), 5(moist), 4 (mod.moist)	80.0%
	other	3 (very fresh), 2 (fresh)	20.0%
Drainage class	main	5 (imperfectly), 6 (poorly)	80.0%
	other	4 (mod.well), 3 (well)	20.0%
Presence of mottles	main	depth to mottles averages 15.9 cm	100%
	other	0	0%
Average coarse fragments (%)			16.5%
Average pH value			5.71

*RRL: root restricting layer

moisture regimes are 6 , 5 , and 4. The main drainage classes are 5, and 6. The soil types include SS8 , SS7 , and S8, S9, S7.

Table 34 gives the comprehensive comparisons of soil conditions for all six groups.

Table 34. Comparison of soil conditions for the different groups.

	A	B	C	D	E	F
Main soil type	S3,S4, S5,	S1,S2, S3,	S1,S2,	S7,S8	SS5 SS4	SS8,SS7 S8,S9,S7 S12F
Main DRRL*(cm)	deep >120	deep >120	deep >120	deep >120	shallow 56.7	shallow 56.8
Main MR**	2	1, 2,	0, 1.	4, 5.	0,1,4,	6,5,4
Main DC***	3	2, 3	1, 2,	5	1,2,5,	5,6,
Presence of mottles	no mottles	no mottles	no mottles	aver. 53.93 cm	no mottles	aver. 15.9 cm
Average coarse fragments (%)	7.1	9.6	22.9	13.4	65.9	16.5
pH	6.35	5.89	5.69	6.48	5.57	5.71

* DRRL= depth to root restricting layer
** MR= moisture regime
*** DC= drainage class

Site Index Comparisons between Groups

Average site indices, standard deviations and standard errors of the mean for each of six groups are given in Table 35. Figure 14 shows the scatter of individual site index values around average site index of each of the six groups. Figure 15 uses the values of Table 35 to show average site indices, observed ranges of site index, standard deviations and standard errors of the mean for each of the six groups.

Table 35. Comparisons of average site index, standard deviations and standard errors among the six groups.

group	A	B	C	D	E	F
Average site index (m) X	21.8	20.6	19.6	18.7	18.7	17.8
Standard deviation (m) S1	2.3	1.8	2.1	1.6	2.9	2.2
Standard deviation (X+S1)	24.1	22.4	21.7	20.3	21.6	20.0
Standard deviation (X-S1)	19.5	18.8	17.5	17.1	15.8	15.6
Standard error (m) (S2)	0.7	0.4	0.4	0.4	0.8	0.7
Standard error (X+S2)	22.5	21.0	20.0	19.1	19.5	18.5
Standard error (X-S2)	21.1	20.2	19.2	18.3	17.9	17.1

Standard deviations show how widely individual site index measurements scatter about the average. In contrast, standard errors of the mean merely express the dependability of average site index (Carmean, 1961).

Results, given in Table 35 and illustrated in Figure 14 and 15, showed that :

1. Average site indices for the six groups ranged from a high of 21.8 m (group A) to a low of 17.8 m (group F). Thus the average had a range of 4.0 m while, in contrast, within groups individual site index values ranged as much as 11.0 m.

2. Each of the six groups had large standard deviations and standard errors of the mean. These results indicate a wide variation of site index within each group. Overlapping of standard deviations and standard errors of the mean indicate that average site indices were not significantly different from each other.

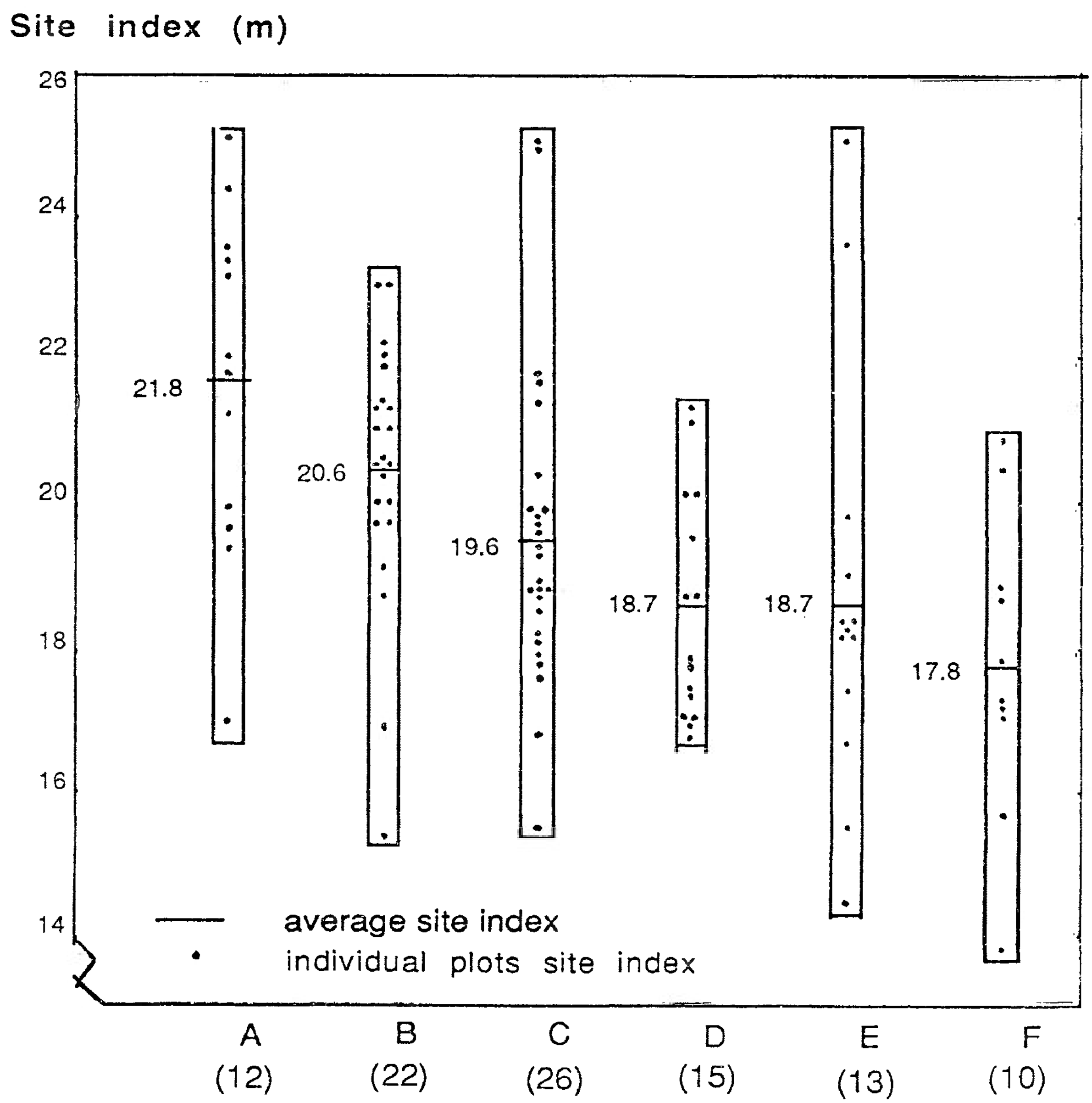


Figure 14. Site index for individual plots and average site index for each of the six groups.

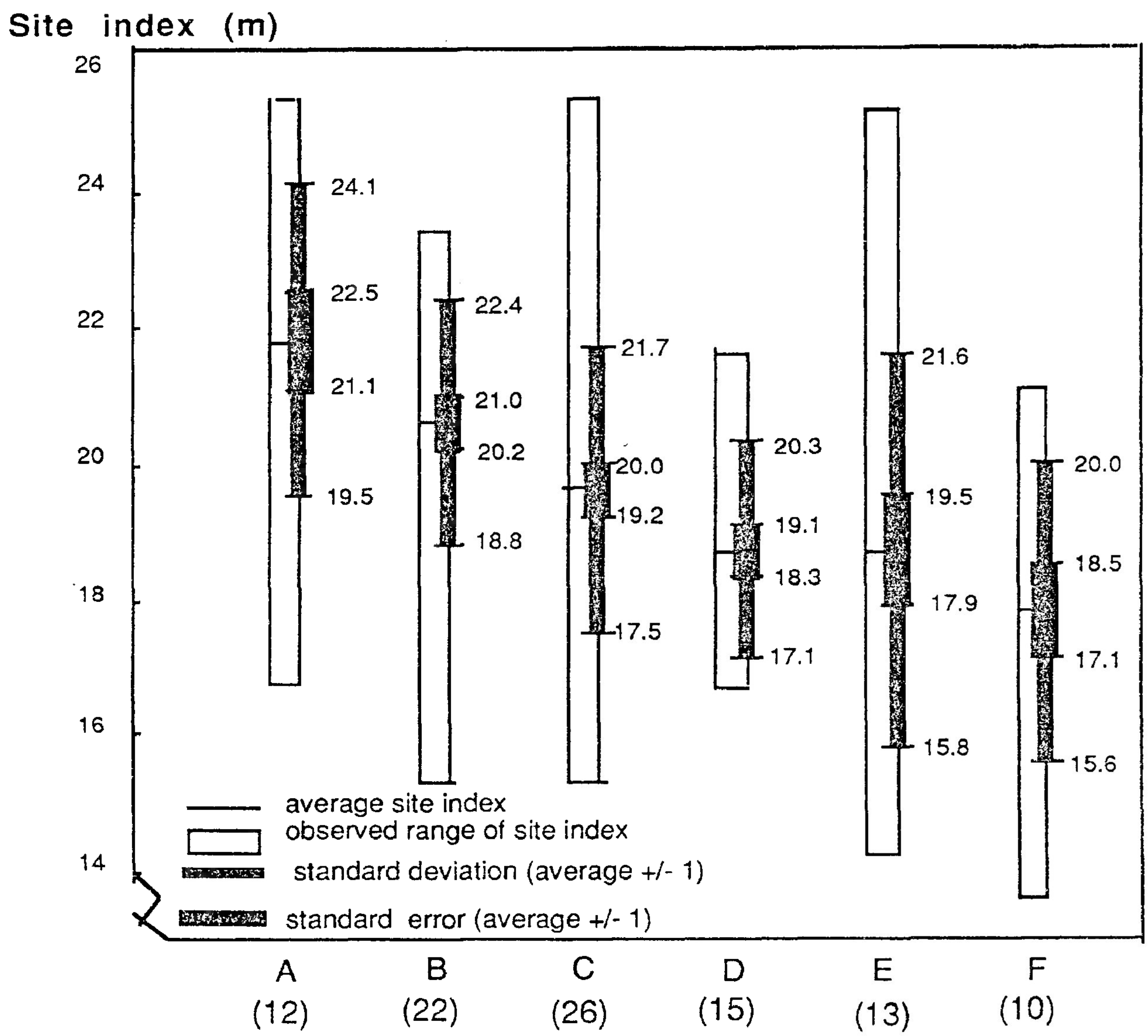


Figure 15. Average site indices, ranges of site index, standard deviations, and standard errors of the mean for each of the six groups.

DISCUSSION

SITE INDEX COMPARISONS AMONG GLACIAL LANDFORMS

The average site index values for glaciofluvial (20.0 m), and lacustrine soils (20.6 m) are not statistically different from each other. However, the average site index value for morainal sites (18.8 m) is about 2 m lower than the average of the other two landform soils.

A wide range of site indices was observed for each of the three landform groups (Table 3). These results indicated that each landform included a wide range of soil and site quality conditions. Results from the regression analyses identified the specific soil conditions closely associated with the observed wide range of site index within each landform group.

For example, the 35 morainal soils contained large amounts of coarse fragments. The coarse fragment content of the C horizon showed that only 14 % of the plots had less than 20% coarse fragments, about 42 % of the plots had a coarse fragment content between 20-40 %, and about 10 % of the plots had a coarse fragment content greater than 80 % (Table 36). In contrast, the plots in the glaciofluvial landform and in the lacustrine landform had coarse fragments less than 20 %. Regression analysis showed that the coarse fragment content was a very significant negative factor for aspen height growth, thus the average site index on morainal landform soils is possibly less than that for the glaciofluvial and lacustrine landform soils.

Table 36. Coarse fragment content of the C horizon shown for morainal landform soils.

coarse fragments %	< 20	20-40	40-60	60-80	> 80	total
Number of plots	5	15	6	6	3	35
% of plots	14	42	17	17	10	100

Glaciofluvial Landform

Regression analysis showed that only three of the screened variables Q13 (clay in C horizon), Q21 (depth to root restricting layer) and Q36 (drainage class) were significantly correlated with site index. The depth to root restricting layer was the most significant variable of the three. The preliminary regression included 5 variables explaining 63 percent of the variation in site index (Table 9), the final regression equation slightly increased R^2 value (0.63 to 0.65) (Table 12). The final equation only included two variables (depth to root restricting layer and drainage class). Thus, this final equation is much easier to use in the field. The transformation and interaction variables included in the final equation expressed the curvilinear relationships existing between aspen site index and both depth to root restricting layer and drainage class.

Soils having shallow depths for rooting are poorer sites for aspen height growth, probably because shallow soils have less available moisture and nutrients. The final regression equations for the morainal and lacustrine soil groups also included an expression for soil depth.

The final equation for the glaciofluvial landform included a variable for drainage class, but did not include an expression for soil texture. The probable reason is that the glaciofluvial group included mostly sandy soils. Also relations between site index and soil texture probably are indirectly expressed by drainage class.

Preliminary results for the morainal and lacustrine soils showed that aspen site index was closely related to silt plus clay, and to clay content. Glaciofluvial soils usually ranged from very dry coarse sands to moist, loamy, very fine sands. For this landform, very rapidly drained soils are related to coarse sandy soils; moderately drained soils probably are related to fine sand or silty soils. Consequently, drainage classes 3 and 4 indicate greater amounts of available soil moisture than occur in drainage classes 1 and 2. Thus drainage classes 3 and 4 indirectly indicate finer-textured soils such as very fine sand or silt or silt plus clay texture. In contrast, drainage classes 1 and 2 indicate drier coarser-textured sandy soils. Thus for the glaciofluvial soils, even though soil texture and soil moisture variables do not appear in the final equation, their effects still are expressed by other variables.

Morainal Landform

For the morainal soils eight of the screened variables had a significant simple correlation with site index (Tables 4 and 8). Coarse fragment content of the C horizon was by far the most important of the independent variables. The preliminary regression included 5 variables and explained 64 percent of the variation in site index (Table 9). The final equation replaced the variables Q26 (Thickness of Cg) and Q31 (depth to mottles) with transformation and interaction terms for the other 3 variables, thus slightly increasing the R^2 from 0.64 to 0.66 (Table 15). The final equation showed that site index increased as depth to root restricting layer increased at a greater rate for sites with lower coarse fragments of the C horizon (Figure 5,6,7). The positive relationship of site index with depth to root restricting layer is expected since better growth is associated with increased rooting depth (Carmean,1975; Pritchett and Fisher, 1987). An increase in coarse fragment content is usually associated with a decrease in site index (Schmidt, 1986; Schmidt and Carmean, 1988). A positive relationship between site index and silt plus clay content of the A horizon is also to be expected because an increase in silt plus clay content is usually associated with increased amounts of available moisture and nutrients and thus increased site index.

Lacustrine Landform

For the lacustrine soils three of the screened variables had significant simple correlations with site index (Tables 4 and 8). The clay content of the C horizon had the highest simple correlation with site index, and the depth to mottles had the second highest simple correlation. The preliminary regression equation included four variables and explained 65 percent of the total variation (Table 9). However, the final equation indicated that Q12 (clay content of the BC horizon) and Q13 (clay content of the C horizon) were highly correlated, thus one of these variables could be eliminated. Accordingly, Q13 was transformed and was used in conjunction with depth to mottles (Q31), thus only two variables were needed in the final equation, and R^2 was increased from 0.65 to 0.68 (Table 19).

The final equation containing depth to mottles and clay content of the C horizon indicates that the best aspen sites are on deep soils with heavy-textured C horizons. Probable reasons are that heavy subsoils have a good ability to hold soil water, and a deep depth to mottles indicates well aerated surface soil conditions, thus a deep rooting depth. The positive relation between site index and clay content of the C horizon showed aspen site index is strongly related to the amount of water available for growth. As well, the positive relation observed between site index and depth to mottles showed that water tables too close to the soil surface decreases aspen site quality. The deeper the depth to mottles, the better the site quality for aspen. Shallow depths to mottles probably reduces the available rooting space, and thus reduces available water and nutrients.

Regression results agree with the results of cluster analysis in that moisture regimes 1 and 2 are better sites, and that either dry soils or wet soils are poor sites for aspen.

SOIL TYPE

The goal of the FEC soil type key for Northwestern Ontario is to provide a classification system for potential forest management applications and interpretations (Sims *et al.,* 1990). Classifying forest productivity (such as site index) is one such interpretation. The FEC soil type system is based on soil depth, moisture regime, calcareousness and soil texture. Soil factors closely related to aspen site index are: soil depth, soil moisture regime, soil drainage classes and soil texture. Most of these factors are considered in the FEC soil types, thus soil types that accurately reflect these important site factors should also accurately express aspen site index.

The cluster analysis used in this study showed that FEC soils S3 (fresh/coarse loamy), S4 (fresh/silty-silt loamy) and S5 (fresh/fine loamy) are the best soil types for aspen growth. These soil types mainly represent the fine-textured soils. Coarse fragment content is typically low (less than 20%), and moisture regime is less than class 4. In contrast, soil types poorer for aspen are SS8 (shallow-moderately deep/mottles-gley), SS7 (shallow-moderately deep /silty-fine loamy-clayey) as well as S7 (moist/sandy), S8 (moist /coarse loamy). The poorest sites for aspen are SS5 (shallow-moderately deep/sandy), and SS4 (very shallow soil on boulder pavement). These poorest soil types for aspen mainly represent the shallow soils, and/or moderately moist to very moist soils.

Results of this study show that there is much variation in site index within each cluster group. This excessive variation of site index was indicated by the similiar means for the six groups, wide site index ranges, large standard deviations, and large standard errors of the means (Table

35, Figures 14 and 15). In a normally distributed population, two-thirds of the site measurements will fall within one standard deviation above or below the mean site index (Carmean, 1961). The six cluster groups of this study, except the D group, showed a very wide range for individual site index measurements scattered about the average site index.

The ranges and standard deviation of site indices for each group overlap to such a degree that there are few significant differences among the six groups. Therefore, presently we cannot accurately estimate aspen site index using these six groups. Therefore, the use of these six groups is not recommended for estimating site quality for trembling aspen in Northwestern Ontario.

Probably the reason for such wide ranges of site index within the six soil groups is that soil features that are closely related to aspen site quality are not well defined in the six groups, or in FEC soil types. For example, regression analyses from this study show that depth to root restricting layers and coarse fragment content are closely related to aspen site index. However, the FEC soil type descriptions do not clearly describe these critical site features. Therefore, wide variations of these critical site features within soil types may also lead to wide variations of site index within soil types and the six soil groups.

THE MAIN SITE FACTORS ASSOCIATED WITH ASPEN SITE INDEX

Site quality is largely determined by soil properties which influence the quality and quantity of growing space for tree roots (Coile, 1952). Both regression and cluster analysis of this study indicate that the site factors: soil depth, coarse fragment content, soil texture, and soil moisture are significantly related to site index for trembling aspen.

These factors influence the aeration and rooting space of aspen and thus determine aspen site quality.

Soil Depth

Various measures of soil depth have been associated with site quality in many soil-site studies (Coile, 1952; Carmean, 1975). Fourteen soil depth variables were examined in this study as expressions of effective soil depth for rooting (Table 2). Soil depth measurements are easy to obtain from field measurements. Such variables include depth to bedrock, depth to root restricting layer, depth to mottles, and depth to gley. These variables effectively express depth to root restricting layers, and also effectively express volume of soil available for root development.

The significant soil depth factors in this study were depth to root restricting layer and depth to mottles. These two variables were significant when all plots were combined for analysis, and also when plots were separately analyzed by landform groups (Table 4). All of the simple correlations for site index with these two depth variables are positive. The final regression equation for each of the three landforms contain a soil depth variable from these two variables. For example, equations G3 (Table 12) for glaciofluvial sites and equation M5 (Table 15) for morainal sites include a variable expressing depth to a root restricting layer; equation L4 for lacustrine sites (Table 19) contains a variable expressing depth to mottles. The regression coefficients for these soil depth variables are positive, indicating an increase in site index with increasing soil depth.

The cluster analysis showed the same results in that better sites for aspen growth are deep soils, without mottles in horizons occupied by roots.

Coarse Fragment Content

Content of coarse fragments is the most significant factor related to a decrease in aspen site index for the morainal soil group (Table 15. Figures 5 to 7). This negative relationship was found for the various soil horizons, but in the final regression equation coarse fragment content of the C horizon was the most important. This trend of decreased site index with increased coarse fragment content was also found for jack pine growing on morainal soils (Schmidt, 1986; Schmidt and Carmean, 1988). Poorer growth of aspen is related to coarse fragment content because coarse material in the soil reduces the effective volume of rooting space, and thus reduces the supply of moisture and nutrients important for tree growth (Ralston, 1964).

Soil texture

This study shows that soil texture was closely related to aspen site index. Soil texture was measured in this study in terms of percentages of sand, silt, clay, and silt plus clay for four soil horizons resulting in a total of 16 texture variables that were tested by regression analyses.

Simple correlations showed that many texture variables were significantly correlated with site index (Table 4). For all four horizons, the percentage of sand was negatively correlated with site index, percentage of silt and clay was positively correlated, and percentage of silt plus clay also was positively correlated with aspen site index. The positive correlation between aspen site index and silt plus clay content agrees with many aspen soil-site studies (Stoeckeler, 1948, 1960; Heeney *et al.,* 1980; O.M.N.R., 1988). These studies showed that growth of aspen is optimum on loams to silt loams having about 60 percent silt plus clay content (Stoeckeler, 1960).

The clear relationships between site index and the soil texture variables were not apparent when the 98 plots for all three landform soils were combined (Table 4). The probable reason is that when the 98 plots were combined, a wide variety of soil textures was also combined. In contrast, soil texture was relatively similar for each landform group, e.g. glaciofluvial soils usually were sandy soils, and lacustrine soils were usually clay soils. Even so, texture does vary within the three landform groups thus some texture variables were significantly related to site index. These significant variables included clay content for both the glaciofluvial and lacustrine landforms, and sand, silt and silt plus clay content of the A horizon for the morainal landform.

Soil Moisture

Soil moisture has been viewed as one of the most important factors in determining forest growth (Gaines, 1949). In this study, soil moisture was expressed in terms of soil moisture regime (MR). Cluster analysis showed that better aspen growth was associated with moisture regime 2 (fresh) and 1 (mod. fresh). Too much water in the soils (MR=6, very moist, MR=5 moist) was associated with poorer aspen site index. On the other hand, the very dry soils (MR=0) were also associated with poorer aspen sites.

Soil drainage class was closely associated with soil moisture regime. The best sites for aspen growth were in drainage classes 2 (rapidly drained) and 3 (well drained). In contrast, drainage classes 5 (imperfectly drained) and 6 (poorly drained) had poorer aspen site indices. Very rapidly drained soils (drainage class 1) are related to dry soils (moisture regime 0). These very rapidly drained soils had somewhat better site indices than drainage classes 5 and 6, but were still poorer than drainage classes 2 and 3.

Regression analysis for glaciofluvial soils showed that good sites for aspen growth were in drainage classes 2 to 4 (Table 13). This means that best growth for aspen occurs on fresh and moderately fresh soils that are well and rapidly drained. Poorly and excessively drained sites did not support good aspen growth. However, aspen does seem to be more tolerant of very rapidly drained soils than of poorly drained soils. This result is similar to the conclusions of Stoeckeler (1948, 1960). The O.M.N.R. (1988) also considers that best growth for aspen occurs on well drained soils having a constant supply of moisture (moisture regimes 2 and 3).

EVALUATION OF TECHNIQUES

Three multivariate statistical techniques were used in this study, including principal component analysis, regression analysis and cluster analysis. Each of these techniques is a very powerful tool for use in soil - site research. Each of these techniques has its own role in soil-site studies. Principal component analysis can be used to eliminate numerous independent variables that are closely associated with each other. Principal component analysis combined with correlation coefficient analysis can be used to select a set of variables that are closely related to site index, but are least correlated with each other. Regression analysis can then be used to develop regression equations, and also for developing trend graphs and site-index prediction tables that quantitatively express relationships between site index and the various significant soil variables. Cluster analysis can roughly relate FEC soil types to site index, and can also relate site index to some soil features, such as depth to root restricting layer, moisture regime, drainage class, coarse fragment content and pH.

Carmean (1975) stated that most successful soil-site studies explain 65 to 85 percent of the variation in site index. The final equations for glaciofluvial, morainal and lacustrine explain 0.65, 0.66 and 0.68 percent of the variation in site index, respectively. The R^2 values of the final equations for these three landforms are acceptable by Carmean's standards.

The results of cluster analysis showed that limitations in this method must be recognized. Results show that most cluster groups had large standard deviations and large standard errors of the mean, thus indicating a very wide range of site index within each group. Even though cluster analysis results are not significant, this method, when combined with regression analysis, indicates fruitful areas of study leading to better definitions of soil types that have less variation in site index, and that also can better define areas of good, medium and poor site index for aspen. Regression analysis identifies specific features of soil and topography that are closely related to site index. These specific site features can then be used for refining or more precisely defining FEC soil types.

RECOMMEDATIONS FOR FUTURE RESEARCH

This study reveals many soil-site relationships for trembling aspen in Northwestern Ontario. The following additional research is recommended:

1. More aspen site plots are needed representing a wider range of soil and topographic conditions. This would include older aspen stands occurring on very good and very poor quality sites; particularly needed are plots representing very poor aspen sites.

2. The multivariate statistical techniques given here for dealing with soil-site studies are very helpful. Principal component analysis, used in this study, is an effective technique for eliminating the numerous closely correlated independent variables. This multivariate analysis technique should be employed in future soil-site studies.

3. Standard deviations and standard errors of the mean are very large for groups defined by cluster analysis, thus indicating that the six groups defined in this study are not significantly different from each other. However, future different cluster analyses are still applicable for soil-site studies. Multiple regression results can be used with cluster analysis methods for defining soil groups having less internal variation in site index.

4. Care is needed in landform classification for plots so that each landform contains plots that fall within the landform definition. The establishment of plots in areas having mixed, atypical, or unusual landform conditions should be avoided.

5. This study shows that surface soil features are usually important in regression analysis. These features include depth to root restricting layer or mottles, and coarse fragment content. Accordingly, profile descriptions should accurately describe these surface soil features known to be closely related to site quality.

IMPLICATIONS OF THIS STUDY

Forest site-quality evaluation is a vital part of a complementary framework that involves forest land classification and yield prediction (Carmean, 1977). Forest managers require knowledge about forest land productivity for tree growth in areas having highly variable sites. Forest site-quality includes several direct and indirect methods that offer forest managers tools for estimating and classifying the productive capacity of forest land for growing trees. These tools can be used for designating land areas and tree species for intensive forest management.

This study has the following implications for forest management in Northwestern Ontario:

1. Regional harvesting schedules for trembling aspen stands should give priority to aspen stands located on shallow morainal soils, containing large amount of coarse fragments. These are poor sites for aspen where defect and stand breakup are pronounced. Trees on such sites should be quickly harvested when they are merchantable, otherwise stands will soon be lost by breakup and defect.

2. Stands growing on both poorly drained (drainage classes 5 and 6, moisture regimes 5 and 6) and very rapidly drained (drainage class 1, moisture regime 0) sites are poor sites for aspen, and these stands should be harvested first before they become defective and break up.

3. Poor site aspen stands have slow growth and produce timber with considerable defect. Moreover, aspen stands on poor sites usually have much defect and break up at an early age. Lands that are poor site for aspen should be considered for conversion to conifers. In contrast, good sites for aspen include deep medium-textured soils having few coarse fragments. When good aspen clones are already established on such good sites, they might better be retained for aspen management. The reason is that aspen on such good sites grows rapidly and produces large volumes of high quality products. Aspen on such good sites also maintains height and volume growth longer than on poor sites. An additional reason for maintaining aspen already established on good sites is that conversion to conifers usually is difficult and expensive, thus forest management on good aspen sites might be directed to better management of these established aspen stands.

CONCLUSIONS

This study described relationships between site index for trembling aspen and features of soil and topography in Northwestern Ontario. Soil and topographic characteristics together with site index from stem analysis were measured on a total of 98 plots. Methods of multivariate statistical analysis used were principal component analysis, multiple regression and cluster analysis. Separate regression equations were derived for each of three landforms: (1) glaciofluvial (40 plots); (2) morainal (35 plots); and (3) lacustrine (20 plots). The 98 plots also were clustered into six groups based on their different soil conditions using cluster analysis. Regression and cluster analyses have led to the following conclusions:

1. The main factors significantly related to aspen site index in Northwestern Ontario are depth to a root restricting layer, depth to mottles, coarse fragment content, soil texture, soil moisture regime and soil drainage class. For morainal soils the coarse fragment content is the most significant factor associated with poorer aspen site index. For glaciofluvial soils coarse sandy soils are poor sites for aspen, and increased silt plus clay content is associated with better site indices. For all soils the important soil depth factors were depth to root restricting layer and depth to mottles. Site index increases with increasing depth to a root restricting layer, and the deeper the depth to mottles, the better the aspen site index. Best aspen growth occurs on well-drained soils having a moisture regime of 2 and 1, and drainage classes 2 to 4. Both poorly drained and excessively drained soils are poor sites for aspen.

2. The regression equation (Table 12) for glaciofluvial soils contained two variables--- depth to root restricting layer and drainage class. This equation can be used to construct trend graphs (Figure 3) and a site-prediction table (Table 13) for estimating aspen site index on glaciofluvial soils.

3. The regression equation (Table 15) for morainal soils contained three variables---silt plus clay content of the A horizon, coarse fragment content of the C horizon and depth to root restricting layer. This equation can be used to construct trend graphs (Figure 5 to 7) and site-prediction tables (Table 16) for estimating site index of aspen on morainal soils.

4. The equation for lacustrine soils (Table 19) contained two variables--- clay content in the C horizon, and depth to mottles. This equation can be used to construct trend graphs (Figure 9) and a site-prediction table (Table 20) for estimating site index of aspen on lacustrine soils.

5. The FEC soils S3, S4, S5 are the best soil sites for aspen. These soil types mainly represent the fine-textured soils. In contrast, SS8, SS7, S7, S8, SS5, and SS4 are the poorest sites for aspen. These poor soil types mainly represent shallow soils, and/or moderately moist to very moist soils. However, results based on cluster analysis showed that average site indices were not significantly different among six groups that combine FEC soil types. Results showed large standard deviations and large standard errors of the mean indicating much variation of site index within each defined group. Thus, these groups are not recommended for predicting site index for trembling aspen in Northwestern Ontario. Further studies relating aspen site index to soil types are needed.

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APPENDIX

PROJECT: ____________________

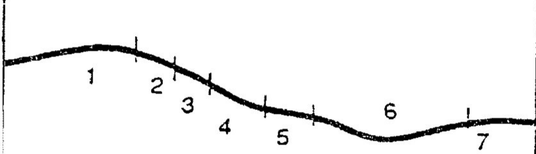
Plot No: __________ Date (D/M/Yr.): __________ Names: __________

Site Index: (m)	No. of Sample:	Mode of Deposition:
bH ______ tH ______	Trees: __________	F GF L E M O R BP

					mottles				structure			coarse frag. %						
sample #	horizon	depth (cm)	texture	color	color	ab	si	co	grade	class	kind	total	gravel	cobbles	stones	ab	si	comments

Topography	
slope length (m)	
upslope length (m)	
slope (%)	
aspect (%)	
site surface shape convex str concave	

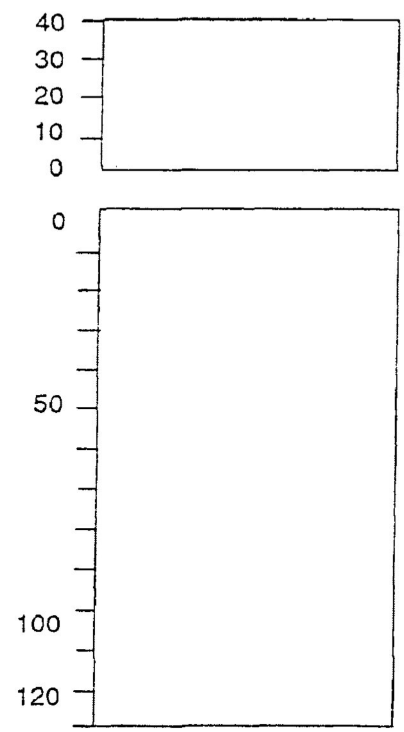
SITE POSITION



moisture regime	
drainage class	
pore pattern	
family particle size	
forest humus form (1-15)	
soil classification	
excavation method shovel auger	
STRATIFICATION	
soil stratified (y/n)	
Particle size discontinuity	
lenses	
bands	

Depth from Surface to:	(cm)
bedrock	
water table	
seepage	
telluric water	
carbonates	
faint mottles	
distinct mottles	
prominent mottles	
grey gley	
bottom of zone of :	
maximum rooting	
avg. rooting	
Microtopgraphy (1-7)	
FEC Soil Type	
FEC Veg Type	
surface stones (%)	
surface bedrock (%)	

schematic soil profile



Comments: